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THE ROLE OF POLYELECTROLYTES IN FILTRATION PROCESSES

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16. ABSTRACT

This research has been conducted (1) to determine how destabilizing chemicals function in enhancing the effectiveness of filtration processes, and (2) to consider selected applications of destabilizing chemicals in filtration for the treatment of wastewaters. The investigations have included (1) laboratory experiments using polymers and latex suspensions, (2) laboratory and pilot plant experiments using alum, polymers, and trickling filter effluent, and (3) laboratory experiments using polymers and calcium phosphate suspensions.

The report includes conclusions regarding the mechanisms of polymer action in filtration, the results that can be obtained using polymers as filter-aids, and the application of this knowledge of the design of filtration processes for wastewater treatment.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described here presents results of an investigation to determine applications of destabilizing chemicals in filtration for the treatment of wastewaters.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

REVIEW NOTICE

The National Environmental Research Center--Cincinnati has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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SECTION I

CONCLUSIONS

1. Particles are removed from suspension in wastewater filtration by being transported to the vicinity of the external surface of the filter grains, and then attaching to the solid material at that interface. Particle transport is determined by the design and operation of the filters, and by the size and density of the particles to be removed. The attachment within the bed generally requires chemical destabilization in a pretreatment step prior to filtration.
2. Particle transport within the pores of a filter bed is a very effective process in conventional water and wastewater filtration. Given proper chemical pretreatment, conventional filter beds are capable of removing virtually all particles applied to them, regardless of suspended particle size. Viruses (0.01 microns) and biological flocs (100 microns) should be filterable. When effective filtration is not obtained, failure should be attributed to poor chemical pretreatment.
3. Regarding mechanisms of particle transport within filter beds, the following statements can be made:
   a. There exists a size of particles for which the transport (and hence removal) efficiency is a minimum. For conventional filtration practice, this critical suspended particle size is about 1 micron. Nevertheless, sufficient particle transport is provided in these systems to permit effective filtration.
   b. For suspended particles larger than 1 micron, transport within the filter pores is accomplished by sedimentation and (or) simple fluid motion (interception). The removal which results increases with increasing size of the suspended particles.
   c. For particles smaller than 1 micron, transport is accomplished by diffusion (Brownian motion). Removal increases with decreasing size of the suspended particles.

d. Mathematical models for particle transport within filter beds have been developed which are in qualitative agreement with the results obtained experimentally in laboratory systems.

4. The chemical destabilization required for effective filtration is similar to that required for effective coagulation. This chemical pretreatment was observed to be required for effective filtration of all systems considered in this research, including suspensions of latex particles, synthetic calcium phosphate precipitates, and trickling filter effluent.

5. When chemicals are used to provide for the destabilization of suspended particles, jar tests may be used to determine the proper type and dosage of chemical. The optimum dosage in a jar test (a batch coagulation test) is the chemical dosage that will provide the best effluent quality in a filtration process.

6. For many conventional filters, this best effluent quality is produced at the expense of short filter runs due to rapid build-up of headloss. Effective attachment within filter beds requires the use of bi- or multi-media filters, upflow filters, moving bed filters, etc.

7. When polymers are used as destabilizing chemicals, overdosing can occur due to restabilization of the suspended particles. A stoichiometry exists between the optimum polymer dosage and the concentration of material to be filtered from the water.

8. For the cationic polymer series investigated (polyethylenimines), the optimum polymer dosage was independent of the molecular weight of the polymer, but the removal efficiency of filters operated at this optimum dosage increased with increasing molecular weight.

9. For direct filtration, precoating of the filter media is essential for effective removal of suspended particles. Precoating is also useful even when prior coagulation and settling are employed, since it greatly reduces the initial "ripening" period during a filter run. It is probable that precoating can be accomplished during the backwashing step of a conventional filtration cycle.

10. For a properly conditioned influent, filter efficiency is, to a first approximation, independent of the concentration of suspended materials. Direct filtration of low-turbidity systems is feasible and can lead to lower chemical requirements than when a conventional rapid mix-flocculation-settling-filtration sequence is used. Direct filtration will require instrumentation for adjusting the chemical dosage, and the services of competent operators.
11. The head loss developed within a filter bed varies inversely with the size of the particles removed from suspension. Stated another way, sub-micron particles removed in conventional filters produce much greater head losses than an equal weight of particles of larger size.
12. Trickling filter effluent apparently contains large quantities of sub-micron colloidal material. This is evidenced by (a) the need for large polymer dosages in coagulation and filtration, (b) the shape of the jar test curves in the underdosed region, with some polymer dosages producing increased turbidities, and (c) the excessive head losses produced during filtration.
13. Studies of the direct filtration of trickling filter effluent led to the following conclusions:
    a. Direct filtration without chemical pretreatment and using conventional filters was ineffectual in removing suspended solids, BOD, and TOC.
    b. Direct filtration using conventional filters and a cationic polymer as the sole destabilizing chemical is possible, but polymer dosages are high and head losses are excessive.
    c. Direct filtration using alum for chemical destabilization produces flocs which readily pass through conventional filter beds.
    d. It was not possible to find an anionic polymer capable of use as the sole destabilizing chemical for the filtration of trickling filter effluent.
    e. Alum and an anionic polymer (Purifloc A-23) used in series provided effective destabilization for the direct filtration of trickling filter effluent. Efficient removal of suspended

solids, turbidity, BOD, TOC, and total phosphorus could be achieved.

f. The optimum doses of alum and Purifloc A-23 for producing the best effluent quality in direct filtration could be determined using jar tests.

g. Short filter runs due to head loss build-up occurred using alum and Purifloc A-23 in series prior to conventional filter beds. The use of larger media provided longer filter runs. For the conditions of this research a media size of about 5 mm permitted breakthrough at about the same time as the available head loss was consumed.

14. For the direct filtration of calcium phosphate suspensions prepared at pH 8 to 9.5 in the laboratory, the following conclusions can be made:

a. Direct filtration without chemical destabilization is ineffective in achieving removal.

b. With proper chemical destabilization, 80 to 90% of the phosphorus in the suspensions was removed by direct filtration.

c. It was possible to determine the optimum type and dosage of chemical (a polymer was finally used) for this filtration using jar tests.

15. In any deep-bed filtration process, effluent quality is primarily determined by the chemical pretreatment used. The rate of head loss increase, however, is also affected by the size of the filter media. A suitable design procedure could be to select a pretreatment process which is effective by using jar tests, and then to design filters to treat this destabilized suspension using pilot filtration experiments.

SECTION II

RECOMMENDATIONS

1. The design of filter beds cannot be separated from the design of pretreatment systems without risking serious difficulties when the full-scale filter system is placed into service. No filter should be designed for any application without consideration of the pretreatment that may be required to permit effective filtration. The technology is available to permit a wide range of selection among pretreatment processes (operating costs) and filters (capital costs) for achieving stated objectives for water quantity and quality.
2. Consideration should be given to changing current procedures for designing filters. The engineer could first design the pretreatment system, and then design a filter system to remove the suspended materials which have been destabilized by this pretreatment. If appropriate, several pretreatment-filter bed combinations could be developed and compared on a cost basis. Batch coagulation (jar) tests can be used to provide the basis for the design of the pretreatment system; pilot filtration experiments are then needed to design the filter system.
3. Direct filtration should be considered in the treatment of low turbidity waters, thereby permitting a reduction in chemical requirements. This process requires excellent operation. Present development of instrumentation to provide feedback control of the required chemicals should be continued.
4. The feasibility of reducing excessive head losses in some direct filtration processes by providing flocculation without sedimentation should be investigated.
5. Precoating of filter beds by the addition of appropriate chemicals during backwashing should be considered in the design and operation of filter systems.

6. The methods of backwashing filter beds containing large media (5 mm or so) should be investigated.

7. Pilot plant experiments of the direct filtration of calcium phosphate suspensions should be conducted. These investigations should use polymers as filter-aids, and use the pH range 8 to 9.5.

SECTION III

INTRODUCTION

Objectives and Scope

This research has been conducted (i) to determine how destabilizing chemicals function in enhancing the effectiveness of filtration processes, and (ii) to consider selected applications of destabilizing chemicals in filtration for the treatment of wastewaters.

The investigations have included (i) laboratory experiments dealing with the effects of polymers on the removal of colloidal and suspended particles from aqueous suspensions by packed-bed filters, (ii) laboratory and pilot-plant experiments dealing with the direct filtration of trickling-filter effluent from the wastewater treatment plant in Chapel Hill, N.C., and (iii) laboratory experiments dealing with the effects of polymers on the filtration of suspensions of calcium phosphate. Associated with all these filtration experiments were investigations of the effectiveness of polymers and other chemicals as destabilizing agents for the suspended materials to be removed by filtration. Some limited experiments to delineate the mechanisms of this destabilization were also conducted.

The approach used in this research is based upon a model for water and wastewater filtration which has been developed during the past few years (1-6). A brief summary of this model is included in this report to outline the rationale used in developing the experimental program.

The Filtration Model

The filtration of suspended and colloidal particles from a water or wastewater can be considered as involving two separate and distinct steps: (i) the transport of the suspended particles to the immediate vicinity of the filter grains, and (ii) the attachment of the suspended particles to the filter grains or to another particle which has previously been deposited

in the bed (1, 7). When viewed in this perspective, filtration and coagulation processes are quite similar. Previous investigators have evaluated the overall rate of a coagulation process by determining the rate at which collisions occur between particles by fluid motion (orthokinetic flocculation) and by Brownian diffusion (perikinetic flocculation), multiplied by a "collision efficiency factor" which reflects the ability of chemical coagulants to destabilize colloidal particles and thereby permit attachment when contacts occur. A similar approach is used herein to describe filtration. Efficient particle removal requires (i) that the filter bed be designed and operated to provide sufficient contact opportunities and (ii) that the particles to be filtered be rendered unstable or "sticky", usually by the addition of an appropriate type and dosage of chemical either directly to the filter influent or in a prior coagulation process.

The Transport Step

Based on theories developed and tested in the field of air filtration (8), a model for the transport step in water and wastewater filtration has been proposed (2) and developed (3-5). Three physical mechanisms were found to be significant in such processes, viz., interception, sedimentation, and Brownian diffusion. The relative importance of these mechanisms depends upon several physical parameters, the most significant of which can often be the size of the particles to be filtered from suspension. Based on this model and some preliminary experiments, the following conclusions have been reached:

1. Both theory and experiment show that there exists a critical size at which the suspended particles have a minimum contact opportunity and hence a minimum removal efficiency. This critical suspended-particle size is in the order of one micron.
2. For suspended particles which are smaller than this critical size, filter efficiency increases with decreasing particle size. Effective particle transport is provided by Brownian diffusion. This permits the conclusion that a conventional rapid sand filter provides ample contact opportunities for the removal of viruses (ca. 0.01 to 0.1 microns in size). Some authors have mistakenly concluded that such transport is not possible (9, 10).

3. For particles larger than the critical size region, sedimentation and interception combine to produce sufficient contact opportunities so that efficient removal is achieved in conventional filter beds when attachment is effective. Filtration efficiency increases with increasing suspended-particle size in this region.

The important work of FitzPatrick and Spielman (11, 12) should also be noted. These investigators have developed a combined physical-chemical model which includes particle transport and suspended particle-filter media interactions. This model is conceptually more complete than the work reported here.

Some useful similarities exist between particle transport in coagulation processes and in filtration processes. Particle transport in both processes can be considered separately in two distinct regions (e.g., orthokinetic and perikinetic flocculation). In both processes diffusion controls the transport rate for particles smaller than about 1 micron (e.g., perikinetic flocculation). In both cases mathematical models are available for making quantitative estimates of the effects of pertinent parameters on the transport rate in either region. Smoluchowski's equations as extended and applied by Camp (13) provide a quantitative basis for the design of flocculators; Yao's model has the potential of providing a similar base for the design of filters (3).

An important difference arises in comparing coagulation and filtration processes. The detention time which must be provided to achieve a given degree of aggregation by coagulation increases as the concentration of particles to be aggregated decreases. In contrast, the theoretical model for water and wastewater filtration (3) indicates that removal efficiency in filtration, to a first approximation, is independent of particle concentration. Theory and laboratory experiments (5) indicate that a conventional sand bed can effectively remove particles of any size if the attachment step is effective. As a result, filtration without prior coagulation and sedimentation but with direct polymer addition may offer economies for the removal of colloidal particles from waters containing low but objectionable concentrations of colloidal materials.

The Attachment Step

The attachment step is affected by both physical and chemical factors. The significance of some chemical parameters has been demonstrated by several investigators. Conley and Pitman observed that the addition of a polyacrylamide to the filter influent markedly improved the removal of alum floc particles (14). More recently Tchobanoglous demonstrated that cationic polyelectrolytes can be used as filter aids to enhance the removal of suspended particles from secondary effluent (15). These improvements in particle attachment are due to the significant changes brought about by polyelectrolytes in the colloid-chemical characteristics of filter influents. Despite such remarkable effects, little is known about selecting the type and dosage of filter aids. The significance of the molecular weight of the polymers in enhancing the filter performance and the mechanism(s) of filter-aid action are not known. The process is not well understood and no comprehensive conceptual models are available.

Experiments reported in this report were designed to test the proposal that a better understanding of the role of chemical parameters in particle attachment in filtration could be obtained by considering the chemical aspects of filtration and coagulation as analagous. At present levels of knowledge of colloid chemistry, the similarity between the attachment step in filtration and coagulation cannot be shown in mathematical terms. The concept, however, becomes more evident by considering that in both processes the particles should be made "sticky" (destabilized) so that they may attach to each other or to the filter grains upon contact.

At the interface of a liquid phase with solid particles such as the colloids found in natural waters, a diffuse layer of charges exists. When two colloidal particles are brought into close proximity, the repulsive interaction of their diffuse layers can produce an energy barrier which opposes interparticle attachment. To make the colloidal particles "sticky" or destabilized the potential energy barrier between the contacting particles must be reduced or nullified.

At the beginning of a filtration cycle an energy barrier between the particles and the filter grains can control the attachment of particles to the filter grains. However, as filtration proceeds, the suspended particles

coat the filter grains and further removal occurs primarily by the attachment of particles in suspension to particles already deposited on filter grains. Therefore, shortly after the commencement of a filtration cycle, the magnitude of the energy barrier between particles in suspension and particles deposited on filter grains controls the particle attachment in the filtration process. The same interaction also governs interparticle attachment in the coagulation process. Thus, similarities between the attachment steps in coagulation and filtration should be expected.

The destabilization of colloids in a coagulation process frequently involves the adsorption of a destabilizing chemical (coagulant) on the surface of the colloid. Charge neutralization and/or bridging which can result from this adsorption then permit aggregation when contacts occur. The following statements summarize pertinent aspects of this process:

1. An optimum dosage of polymer exists for the coagulation of a given suspension.
2. Overdosing (restabilization) can occur due to charge reversal or saturation of bridging sites.
3. The optimum dosage is directly related to the concentration of colloid.
4. The effectiveness of many polymers is related to their charge and molecular weight.
5. The type and optimum dosage of chemical for a coagulation process can be estimated using jar (batch) tests.

Based on the hypothesis that the effects of destabilizing chemicals are similar in both coagulation and filtration, experiments were performed to test for the existence of these phenomena in filtration. The possible applications of these concepts to the filtration of trickling filter effluent and of calcium phosphate suspensions were then investigated.

SECTION IV

EXPERIMENTAL APPARATUS AND PROCEDURES

The experiments may be divided into four groups: (a) filtration experiments which were designed to evaluate the mechanisms by which polyelectrolytes function as filter aids through the use of latex suspensions, (b) destabilization experiments which were conducted to determine the optimum polymer dosages necessary for coagulating a given suspension and also to study the mechanisms by which polymers bring about the destabilization of colloids, (c) filtration experiments to test the application of these concepts to the filtration of trickling filter effluent, and (d) filtration experiments to test the application of these concepts to the filtration of calcium phosphate suspensions.

Filtration Experiments Using Latex Suspensions

Filtration experiments were conducted in which the filter influents received dosages of polymer equal to, less than and greater than the optimum polymer dosage determined from a jar test. To provide for such experiments a filter apparatus with six identical laboratory filters was constructed (Fig. 1). Characteristics of the filter bed (size and shape of the media grains, bed depth and porosity, surface characteristics of the filter media), characteristics of the operation of the filter (filtration rate, direction of flow, backwashing procedure), and the pH and ionic strength of the filter influent were kept constant. The size and concentration of the suspended particles and the dosages and molecular weight of the polymers added to the filter influent were varied in a controlled manner. The six filters were operated in parallel in the conventional downward direction at a constant rate of 2 gpm/sq. ft. During each run one of the filters did not receive any polymer and served as a blank, two of the filters were underdosed, two were overdosed, and the sixth filter received a continuous polymer dose equal to the optimum dose determined from a jar test. The similarities between filtration and coagulation were then determined by

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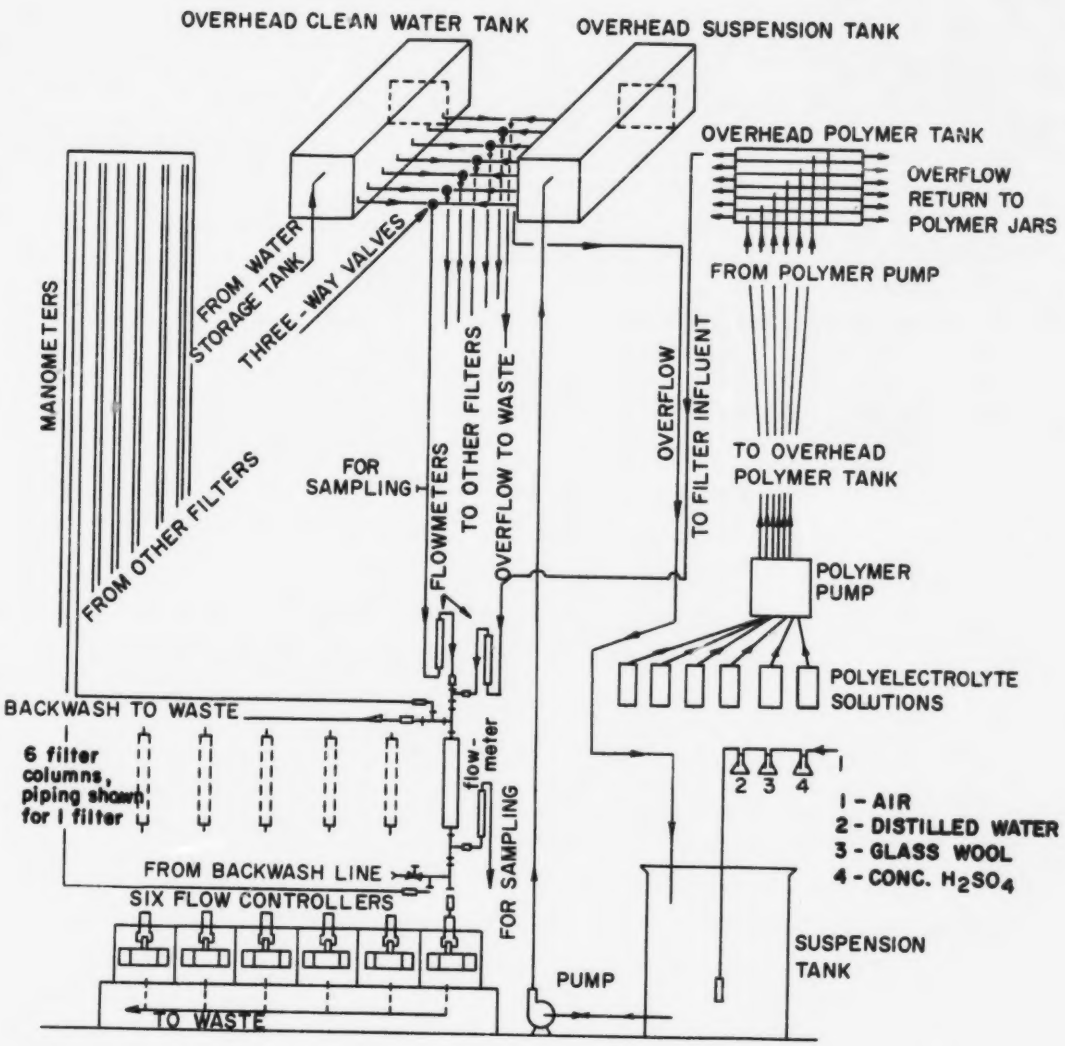

Figure 1. Schematic Diagram of Filter Apparatus, Laboratory Experiments.

comparing the performance of these filters with each other and with the results of jar tests conducted on the same suspension.

Laboratory filters were made of plexiglass tubes having an internal diameter of 2.63 cm. Glass beads (class B, Minnesota Mining and Manufacturing Co.) with a mean diameter of .38 mm and a standard deviation of .04 mm were used for filter media in most of the filter runs. The bed depth and porosity were 14 cm and 36 percent respectively. Initial experiments used uncoated media. Subsequently the filter beds were precoated with a solution of the filter-aid prior to use. The precoating was found necessary for the reduction of a long ripening period which was observed when uncoated filter beds were employed.

Latex beads (Dow Chemical Co.) with mean diameters of 0.109, 1.099 and 7.6 microns were utilized for the influent suspensions. These sizes were selected to provide for evaluating the effectiveness of the continuous addition of polyelectrolytes in both "orthokinetic" and "perikinetic" filtration as well as at the critical particle size. Demineralized water was used for diluting the concentrated latex suspensions provided by the manufacturer. Sufficient sodium chloride and sodium bicarbonate were added to the demineralized water to provide a concentration of 10^{-3} mole/l of each in the final latex suspension. The suspension was brought in equilibrium with the laboratory atmosphere by air agitation. The temperature in the laboratory was almost constant, 27°C $\pm$ 1, during the entire period of the investigation. The pH of the suspension was approximately 8.2.

Five homologs of polyethylenimine (PEI series, Dow Chemical Co.) with molecular weights of 600, 1200, 1800, 40-60,000 and 50-100,000 were used as filter-aids. In a few filter runs Cat-floc (Calgon Corporation) and Primafloc C-7 (Rohm and Haas Company) were utilized. All of these polymers are cationic. To reduce the adsorption of these polymers on glassware used in polymer preparation, the glassware was coated frequently with Siliclad (Clay Adams Co.).

A portion of the filter effluent was collected at appropriate time intervals in a test tube for analysis. Absorbance measured with a Beckman Model DB Spectrophotometer was used to determine the latex concentration in

the effluent. Measurements were made at wavelengths of 270, 490, and 700 mμ for suspensions of .109, 1.099 and 7.6 μ latex particles respectively. The absorbance of the suspensions was observed to be a linear function of particle concentration, and hence the ratio of the optical density of the filter effluent and influent was used as an index of the fraction of the particles remaining in the filter effluent. The absorbance in such systems is affected by particle size, so that the existence in the filter effluent of particles which might have grown in size during the course of filtration can reduce the accuracy of this evaluation. However the possibility of significant particle growth is believed to be very small (6).

Filters were equipped with piezometer tubes above and below the beds of media. The head losses across the filters were measured at the beginning of each experiment, and at frequent time intervals during the filter runs.

Destabilization Experiments

Destabilization experiments were conducted to determine the significance of charge neutralization and/or bridging in bringing about the destabilization of colloidal particles in filtration. It was intended to compare the magnitude of the negative charge existing on suspended particles with the positive charge existing on that quantity of polyelectrolyte necessary for optimum destabilization of these suspended particles. Such a comparison was expected to provide some evidence for determining the dominant mechanism(s) of polyelectrolyte action. To accomplish this, the optimum polymer dosage required for the destabilization of a given suspension, the charges of the suspended particles, and the charges of the polymer used for particle destabilization were determined.

The optimum polymer dosage was determined by conducting jar tests using a six-position magnetic stirrer. The polyelectrolyte was added to the suspension under vigorous agitation. This rapid stirring continued for 2 minutes followed by an appropriate period of slow stirring. The residual light absorption (absorption by the suspension after coagulation and settling) was used as the index of the extent of particle aggregation.

Absorbance measurements were made as described previously.

The surface charge of the latex particles is due to an anionic emulsifier physically adsorbed on the particle surface and to the initiator anion chemically bonded to the starting point of the polymer chains (16). Although the exact chemical natures of the emulsifier and initiator anions have not been reported by the latex manufacturer, the literature suggested that oleic acid and the persulfate ion respectively might have been employed (16). Organic acids such as oleic acid have pK values of about 4.8 (17) and the sulfate radical would have a pK of about 1.7. The pH of a dilute latex suspension was found to be about 6.0. Therefore, it seemed plausible to measure the charge of the latex particles due to the emulsifier anion by titration of a latex suspension with an acid. Conductometric titration was employed using a Serfass Model RCM 15 B1 conductance bridge with a platinum electrode having a cell constant of .098. The conductivity measurements were conducted in accordance with the procedures described in Standard Methods (18). Hydrochloric acid was used as the titrant.

The charge of the latex particles due to the initiator could not be determined by this method. This charge is so small that the end point of the conductometric titration is heavily shadowed by the interference of other ions existing in the bulk solution. Procedures developed by Vanderhoff et al. (16) were employed for this purpose and followed precisely. The technique utilized exchange resins to remove all interfering ions and to exchange the Na^+ and K^+ cations associated with the sulfate end groups with H^+ ions. The number of these H^+ ions and thus the charge due to the initiator anions can then be determined by a conductometric titration of the exchanged solutions. Dowex 50W cation exchange and the Dowex 1X8 anion exchange resins were used.

Acid-base titrations (17) were used to determine the number of charges on the polyethylenimine molecules. The technique is based on the principle of electroneutrality in the polymer solution. If p^{n+} is the total number of positive charges on a given amount of polymer at a given pH, Na^+ and Cl^- the amount of charge due to the addition of base and acid during the titration, V the total volume of the solution, and if A_o^- and C_o^+ are the total equivalent amounts of anions and cations initially present in the polymer

solution, one may write the following:

$$C_o^+ + p^{n+} + V \cdot H^+ + Na^+ = Cl^- + V \cdot OH^- + A_o^- \qquad (1)$$

If A_o^- and C_o^+ are known, then p^{n+} at any given pH can be determined from the above equation.

Sodium and potassium were considered as the only cations that might exist in the polymer stocks. Correspondingly, chloride, sulfate and nitrate were considered as the probable anions in these polymer stocks. The concentrations of sodium and potassium in the polymer solution were measured using an atomic absorption spectrophotometer (Perkin-Elmer 303). The chloride concentration was measured by potentiometric titration of a polymer solution with silver nitrate. A Corning pH meter model 12 equipped with glass and silver-silver chloride electrodes was used. The concentration of sulfate anion was measured by a turbidimetric method as described in Standard Methods (18). In this method, sulfate ion is precipitated in a hydrochloric acid medium with barium chloride in such a manner as to form barium sulfate crystals of uniform size. The Beckman Model DB spectrophotometer was employed for measuring the absorbance of the resulting barium sulfate suspension. Nitrate concentrations were determined by the brucine method following the procedures listed in Standard Methods (18). The reaction between nitrate and brucine yields a sulfur yellow color which can be analyzed by colorimetric methods. The Beckman Model DB spectrophotometer was used.

Titration of polymer solution was begun by addition of enough standard hydrochloric acid to a given polymer solution to lower its pH to about 2. The resulting solution was then titrated with standard sodium hydroxide under a nitrogen atmosphere. The pH value was measured after each addition of a suitable increment of the titrant. The polymer charge at each pH was then calculated by substituting the data obtained into Equation 1.

Filtration of Trickling Filter Effluent

Laboratory Experiment

Initial experiments of wastewater filtration used the laboratory filter apparatus described previously (Figure 1). Effluent from the Mason Farm Wastewater Treatment Plant, Chapel Hill, N.C., was collected and transported to the School of Public Health for use in the filtration experiments. Characteristics of the plant and its waste are described in a subsequent section of this report.

Several polymers were tested in jar tests for their potential as filter aids. Primafloc C-7 was selected for further study. Filter beds were precoated with polymer prior to each run. Filter beds were comprised of coarse sand with a size of 1.3 mm (geometric mean of adjacent sieve sizes) and had a depth of 5.5 inches. Filter runs used polymer applied continuously at the optimum dose (based on jar tests), at an "underdosed" concentration, and at an "overdosed" concentration. One filter received no polymer after the precoating, and served as a blank.

Pilot Plant Experiments

A filtration apparatus comprised of four filters and associated appurtenances was constructed (Figure 2). Secondary effluent was pumped continuously from a secondary clarifier at the Mason Farm Treatment Plant (Chapel Hill, N.C.) to a fifty-five gallon drum. A submersible pump located inside a screen housing at mid-depth in the drum was used to pump the secondary effluent to one compartment of a small constant head tank located above the pilot filters. Secondary effluent was then withdrawn to be treated by the pilot filter apparatus after the appropriate chemical destabilization. The overflow from the constant head tank was discharged to waste as was the overflow from the drum. Pertinent characteristics of the secondary effluent are presented in Table 1, together with a description of the raw sewage received by the Mason Farm treatment plant. This treatment facility, a major part of the UNC-CH Waste Water Research Center, is a conventional high-rate trickling filter plant.

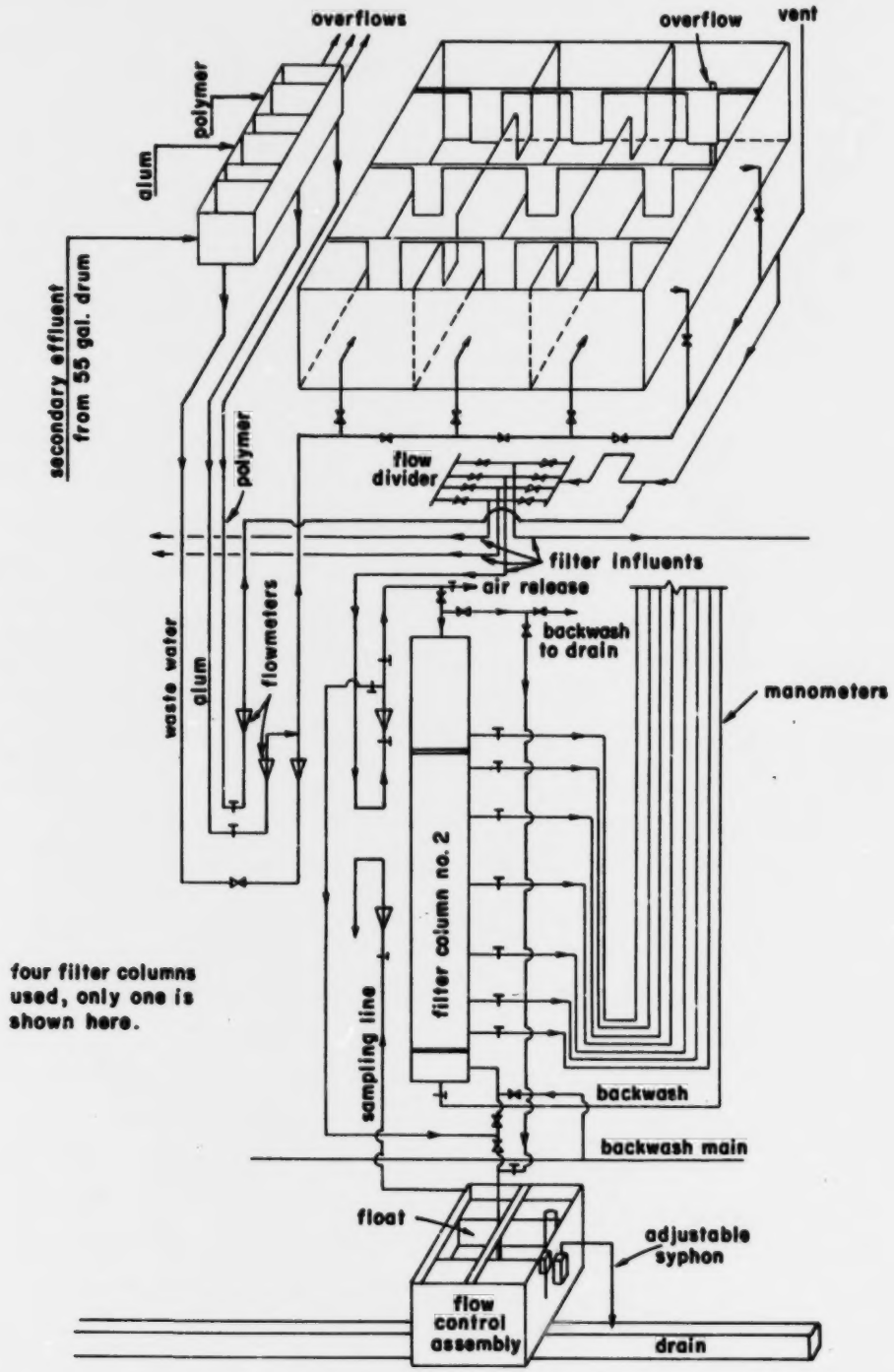

Figure 2. Schematic Diagram of the Apparatus, Pilot Plant Experiments

TABLE 1

WASTEWATER CHARACTERISTICS

(after Hanson et al. (20))

TABLE 1

	Influent	Effluent
Flow (MGD)	2.77	
BOD_5 (mg/l)	172	43.5
Suspended Solids (mg/l)	245	60.
Total Phosphorus (mg/l)	11.8	9.2
Total Dissolved Phosphorus (mg/l)		5.85
Total Organic Carbon (TOC)	178	61.1

Based on a series of jar tests, aluminum sulfate (reagent grade $Al_2(SO_4)_3 \cdot 18H_2O$, hereafter termed alum) and Purifloc A-23 (Dow Chemical Co.) were selected as destabilizing chemicals. Purifloc A-23 is a negatively-charged polyelectrolyte with a molecular weight in the order of ten million (manufacturer's description). Alum was used as the first coagulant or filter-aid; Purifloc A-23 was added to destabilize further the flocs which were formed by alum addition.

Alum stock solutions (31.5 gm/l) were prepared in five-gallon carboys by dilution with Chapel Hill tap water. The alum solution was then pumped to a second and separate compartment in the small influent constant-head tank (Figure 2). An appropriate quantity was withdrawn to mix with the filter influent; the overflow from the constant-head tank was returned to the carboy containing the alum stock solution. Purifloc A-23 stock solutions (0.1455 gms/l) were also stored in five-gallon carboys. To facilitate dissolving the polymer, sufficient powdered Purifloc A-23 to prepare 19 liters of stock solution was added to about 75 ml of methanol in a one-liter bottle. While providing constant agitation, 500 ml of tap water were added to the polymer-methanol suspension. This mixture was stirred vigorously until the polymer dissolved, after which it was poured into the five-gallon carboy and diluted to 19 liters with tap water. During a filtration run, stock polymer solution was pumped to a third and separate compartment in the small constant-head tank (Figure 2). An appropriate quantity was withdrawn to add to the secondary effluent-alum mixture. Overflow from the constant-head tank was returned to the carboy containing the polymer stock solution. The secondary effluent, alum, and polymer flows were metered individually using flowmeters. It was later found that the methanol used to dissolve the polymer contributed soluble BOD and TOC to the filter influents.

Provision was made to provide a period of slow mixing prior to filtration. The alum-secondary effluent mixture was allowed to flow to a second and larger constant-head tank (Figure 2). This tank was divided into three compartments and equipped with a paddle stirrer.

Flow was in series through the three compartments. Depending upon the number of filters in operation, the filtration rate, and the number of compartments used, the flocculation period could be varied from 10 to 120 minutes. Provision was also made to permit by-passing of the flocculation tank; the latter procedure was used in most experiments. Polymer was added to the effluent from the flocculation tank (or to the by-passed secondary effluent-alum mixture) just prior to filtration (Figure 2).

Four pilot filters were constructed using plexiglas tubes having an internal diameter of 5.5 inches. Filter media were prepared from crushed granite which was screened using sieves made from aluminum sheets and a nail punch set. Sieve openings were uniform (1/32, 1/16, 3/32, 1/8, 5/32, 3/16, 1/4, 9/32, and 5/16 in., or 0.8, 1.6, 2.4, 3.2, 4.8, 6.4, 7.2, and 8.0 mm). Media were sized by using the two adjacent sieve sizes and also by Hazen's count and weigh method (21). A summary of the filter beds and media sizes used in this research is presented in Table 2. For media larger than 3 mm, wall effects were probably not negligible, so that the actual removal by full-scale filters could be even better than that observed in the pilot experiments.

Provision was made to operate the filter in both downflow and upflow directions. Piezometer tubes for measuring head loss were located above and below the beds, and at several points within the beds. Provision for obtaining samples was made above and below the filters.

Filtration was at a constant rate, usually 2 gpm/sq. ft. The flow rate through each filter was maintained constant using a float-operated needle valve controlled by a syphon (6, 22).

Samples were obtained every half-hour from the secondary effluent, the filter influents, and the filter effluents. Each sample was immediately analysed for pH and turbidity. A Hach model 2100 turbidimeter was used for turbidity measurement. Samples were then refrigerated and later analysed for total organic carbon (TOC), five-day biochemical oxygen demand (BOD_5), suspended solids (SS), and total phosphorus (TP). The head loss across each filter was observed at half-hour intervals. Floc penetration was observed visually at hourly intervals.

TOC measurements were performed with a Beckman Model 915 two

TABLE 2

CHARACTERISTICS OF FILTER MEDIA

Media No.	Sieve Openings (in.)		Media Size, Hazen (21) (mm)	Specific Gravity (gm/cu.cm)	Media Depth (in.)	Bed Porosity
	Passing	Retained				
1	2/32	1/32	1.65	2.64	36	0.4
2	3/32	2/32	2.36	2.64	36	0.4
3	4/32	3/32	3.08	2.64	36	0.4
4	6/32	4/32	4.D	2.64	34	0.4
5	8/32	4/32	5.9	2.64	33	0.4
6	9/32	5/32	6.3	2.64	32	0.4
7	10/32	5/32	7.5	2.64	30	0.4

channel carbon analyser using procedures prescribed by the manufacturer. Measurements of BOD_5 and SS were made in accordance with Standard Methods (18). Total phosphorus was determined by the stannous chloride method using the Technicon Auto Analyser (23).

Filtration of Calcium Phosphate Suspensions

These experiments can be further subdivided into three parts: (i) phosphate precipitation tests to evaluate the effectiveness of lime under various conditions, (ii) coagulation tests to evaluate types and dosages of polymers which could provide effective destabilization of calcium phosphate suspensions, and (iii) filtration tests to evaluate the effectiveness of these polymers for the removal of calcium phosphates from suspension by filtration.

Phosphate Precipitation Tests

Precipitation tests were conducted to describe the influence of pH, inorganic carbon, calcium, and fluoride on the removal of phosphate by lime. All experiments were conducted using deionized water and reagent grade chemicals. Initially, sufficient aliquots of stock solutions of $NaHCO_3$, $Ca(NO_3)_2 \cdot 4H_2O$, $KH_2PO_4 \cdot 2H_2O$, and NaF were added to deionized water to give a phosphorus concentration of 10 mg P/l and specified concentrations of inorganic carbon, calcium, and fluoride. The solution was then transferred to 600 or 1000 ml beakers, after which the pH was adjusted to the desired level with HCl or NaOH and maintained constant within $\pm$ 0.1 pH units. The resulting suspensions were rapidly stirred for 2 minutes, and then slowly stirred for an additional 20 minutes unless the effects of time on precipitation were under consideration. Finally, 30 minutes of quiesent settling were provided. Two samples were then withdrawn from each supernatant. One sample was immediately filtered through a membrane filter (0.45 μ), after which the phosphorus remaining in both samples was determined using the vanadomolybdophosphoric acid method (18).

Destabilization Tests

Conventional jar tests were used. Polymers of several types and ranging from 1 µg/l to 100 mg/l were added to calcium phosphate suspensions. Polymers were added either with the other reagents ($NaHCO_3$, $KH_2PO_4 \cdot 2H_2O$, etc.) or two minutes after these reagents had been mixed and rapidly stirred. Two minutes of rapid stirring were provided after polymer addition, followed by 20 minutes of slow stirring (flocculation) and 30 minutes of settling were provided. Residual phosphate with and without membrane filtration was determined as described above.

In some cases electrophoretic mobility measurements were made on the calcium phosphate suspensions, with and without added polymer. A glass Briggs cell was used and the procedures recommended by Black and Smith (31) were followed.

Filtration Experiments

The filtration apparatus used for filtering calcium phosphate suspensions was adapted from that used for filtering latex suspensions (Figure 1). Calcium phosphate suspensions were prepared and stored in a 50 gallon polyethylene tank prior to use. Procedures used were essentially those described previously for the precipitation tests, save that continuous air agitation was used to provide flocculation and to maintain the precipitates in suspension. Filter media were precoated with polymer. The dosages of polymer to be used were selected on the basis of jar tests. One filter received no polymer after the start of a run, one received a continuous dosage of the optimum concentration determined in the jar tests, two filters were underdosed, and two were overdosed. Filter media were uniform sand with a size of 0.9 mm; bed depth was 5.5 inches, bed porosity was 43 percent, and the filtration rate was 2 gpm/sq. ft.

SECTION V

RESULTS AND DISCUSSION

Filtration and Destabilization Experiments Using Latex Suspensions

Filters with Uncoated Media

Typical data obtained during experiments using uncoated filter media are presented in Figures 3-A, B and C. Residual turbidity in jar tests is plotted as a function of polymer dosage (Fig. 3-A); effluent quality and head loss are plotted as functions of filtration time (Figs. 3-B and 3-C, respectively). In these experiments a suspension of .1 μ latex particles was prepared and the optimum dosage of PEI-18 for coagulating this suspension was determined to be .06 mg/l from jar tests (Fig. 3-A). The latex suspension was then introduced into six identical filter beds containing uncoated glass beads. The rate of flow controllers for two filters ceased to function in the early stages of this experiment, so that the results produced by these filters are not considered here.

Filter 1 received no polymer throughout the duration of the run; filter 4 received the optimum polymer dose as determined by the jar test (0.06 mg/l); filter 3 was underdosed (.018 mg/l), and filter 5 was overdosed (0.093 mg/l) for the main portion ($0 < t < 328$ min.) of the experiment. Near the end of the filter run (after 328 minutes of filtration), the polymer dosages were increased by 61 per cent, so that filters 2, 4 and 5 then received 0.029, 0.096, and 0.145 mg/l of polymer respectively.

As may be noted from Figs. 3-B and 3-C, filter 1 which received no polymer also did not remove any latex particles from the suspension. Soon after the beginning of the filtration cycle the latex concentration in the filter effluent approached the concentration of latex in the influent. No increase in head loss across the filter bed was

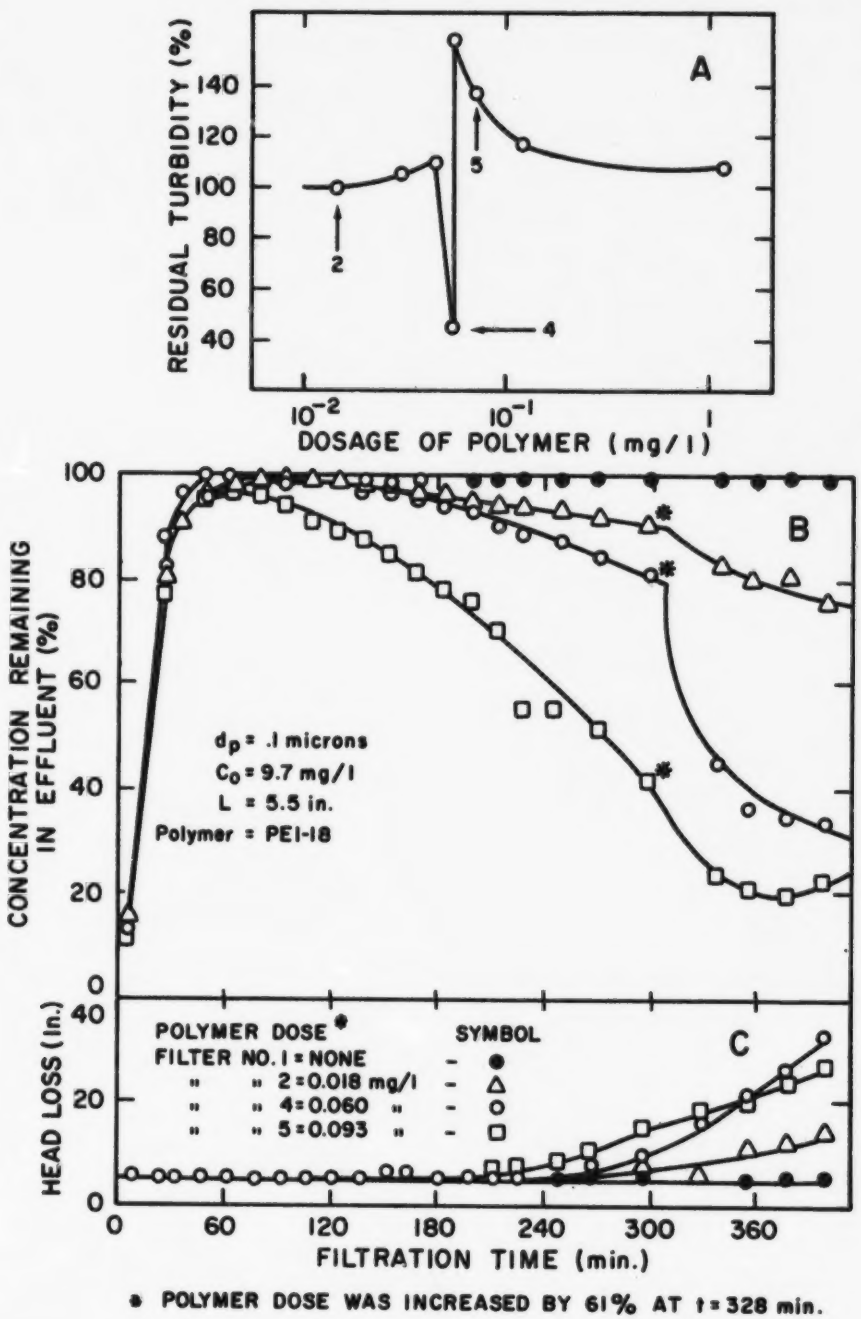

Figure 3. (A,B,C) - Comparison of Jar Test Results (A) with Filter Performance, Uncoated Media (B and C).

observed during this seven hour run.

Prior to changing the polymer dosage ($t < 328$ min.), the removal efficiencies are filter 5 > 4 > 2 (Fig. 3-B). Correspondingly, the rate of head loss increase is filter 5 > 4 > 2 (Fig. 3-C). The occurrence of a long ripening period during which the removal efficiencies of filters 2, 4 and 5 continuously improved is also evident (Fig. 3-B). This long ripening period would have obvious disadvantages in practice and must be reduced or eliminated.

Increasing the polymer dosage during the run produced rapid changes in the performance of these filters. The rate of head loss increase after changing the polymer dosage ($t > 328$ min.) is seen to be filter 4 > 5 $\tilde{=}$ 2 (Fig. 3-C). The removal efficiency of filter 5 deteriorates near the end of the run (Fig. 3-B).

These results indicate that the role of particle attachment can be dominant in the filtration process. Unless provision is made for efficient particle attachment to the filter grains or to the particles previously deposited there, a filter bed will be very inefficient in removing impurities from the filter influent. It may be concluded that the removal efficiency of a filter first increases and then decreases as the applied polymer dose is increased from zero. This indicates that an optimum dosage of polymer for particle removal by filtration does exist and that polymer underdosing and overdosing also occur. In this experiment using uncoated media it appears that the optimum polymer dose in filtration (ca. 0.096 mg/l) is greater than the optimum polymer dose in coagulation (0.06 mg/l). The shape of the experimental curves in Figure 3-B indicates that if the experiment had been continued for a longer period of time, a "ripening effect" might have continued to the point that filter 4 would have produced the best effluent. In other words, the optimum polymer dose for particle removal in filtration might approach the optimum dosage observed for coagulation, as filtration time proceeds. Similar phenomena have been reported by Tchobanoglous (15).

Filters with Coated Media

In order to reduce the long ripening period, a series of experiments

was conducted in which the filter media were coated with polymer prior to the beginning of the filtration cycle. Data obtained in a typical experiment are presented in Figures 4-A, B and C. All experimental conditions were similar to those reported in Figure 3 except that a different polymer (Cat-floc) was used and the filter media were precoated.

When no polymer was added to the influent of a precoated filter bed (filter 1) the effluent concentration reached a plateau soon after the commencement of the filtration cycle (Fig. 4-B). The filtration efficiency remained constant for a short period thereafter and then rapidly deteriorated. No noticeable head loss increase was observed. Similar results have been reported by Yao (3, 5). Filters which received underdosed influent (filters 2 and 3) showed the same pattern of performance.

The latex particles possess a negative charge in water. A residual negative charge persists in an underdosed suspension (6). The attachment of these negatively charged particles to the positively-charged precoated filter grains is manifested by a rather efficient filtration for a very short period at the beginning of the filtration cycle. Soon the precoat capacity for a "monolayer" of suspended particles is exhausted and the removal efficiency deteriorates.

At the optimum polymer dose as determined by the jar tests (.07 mg/l, Fig. 4-A) the effluent concentration (filter 4, Figure 4-B) reaches a maximum soon after the initiation of the filtration cycle and then quickly drops to a low value. Filtration is seen to be so effective that the 7.5 feet of available head are utilized in less than three hours (Fig. 4-C). It is significant to note that this occurs even with particles with a size in the order of .1μ, approximately 1/2000 of the pore openings in the filter bed.

The effluent concentrations of filters 5 and 6 rapidly reached very high values and their removal efficiency remained poor (Fig. 4-B). The increase in head loss across filters 5 and 6 was also small. These data clearly indicate that both underdosing and overdosing occur, that

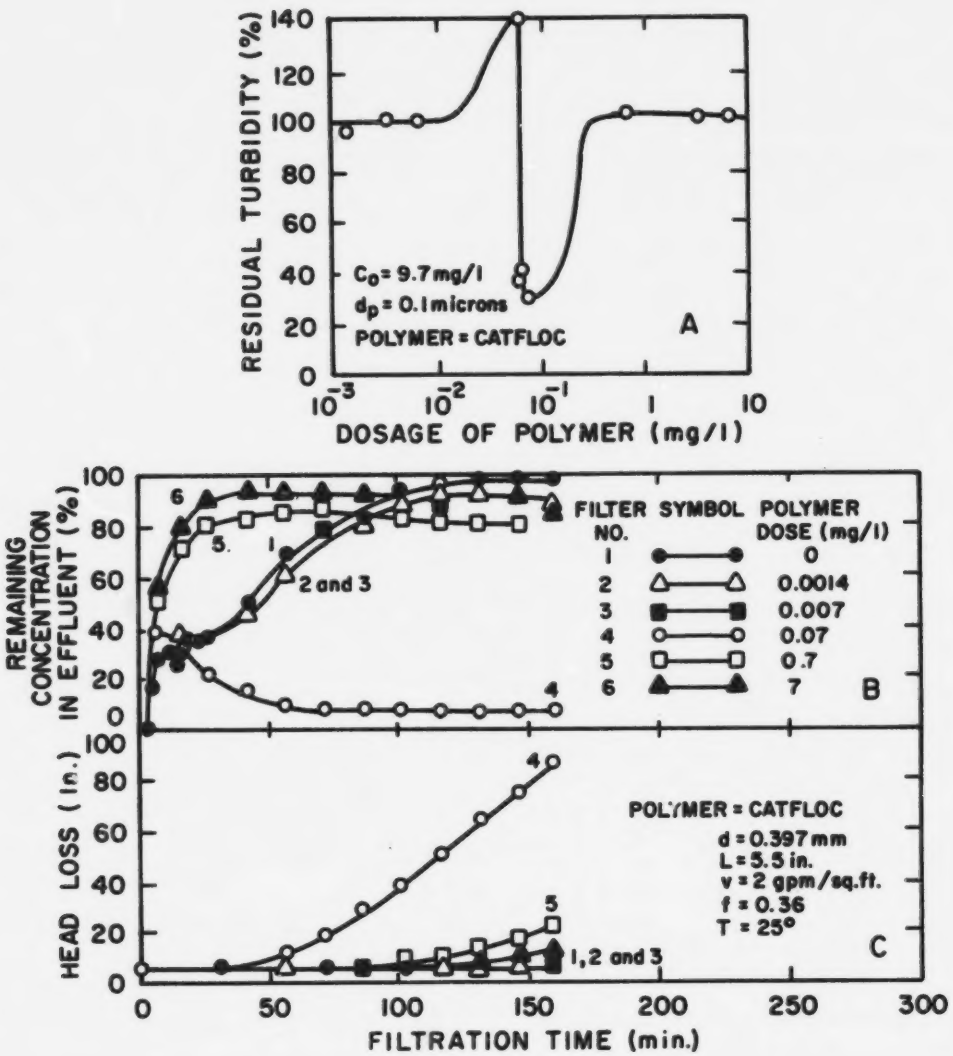

Figure 4. (A,B,C) Comparison of Jar Test Results (A) with Filter Performance (B and C), Precoated Media.

a polymer dosage which provides maximum particle removal by filtration exists, that this polymer dosage when precoated filter beds are used is equal to the optimum dosage determined in jar tests, and that Catfloc, an efficient coagulant for latex suspensions, is an efficient filter-aid for the same suspension. Many other experiments conducted using various concentrations and sizes of latex particles confirmed the validity of these conclusions. The results of these experiments can be found elsewhere (6).

Jar Test Anomalies

While conducting a trial filtration run of a suspension having a low turbidity, it was observed that a filter which had received an optimum polymer dosage determined by the jar test did not produce clear effluent. The sample volume used in each beaker in the jar test for this experiment was 40 ml. The jars were 100 ml beakers which had been coated with Siliclad, the suspension had a concentration of 7.55 mg/l of .1μ latex, and the optimum polymer dosage for coagulation was found to be about .07 mg/l of PEI-18. This was somewhat higher than the expected value. Another jar test was conducted with the same suspension, but using a sample volume of 900 ml in 1000 ml beakers. The optimum polymer dose was found to be 0.025 mg/l of PEI-18, considerably lower than with the smaller beakers. The results of these jar tests are presented in Fig. 5-A. Similar results were obtained when suspensions containing small concentrations of 1.099 μ latex particles were used (6).

The optimum polymer dosage necessary for the maximum particle removal when filtering the above suspension of .1 μ particles was determined by a pilot filter technique. This technique uses the response in filter performance to the changes in polymer dosages. This is very rapid and had a time lag of only about 5 minutes for the apparatus used in these experiments. The results of these experiments are shown on Fig. 5-B. It can be seen that the optimum polymer dosage necessary for filtration is equal to the optimum dosage found from the jar tests (Fig. 5-A) when the larger sample volume was used. Thus, the equality

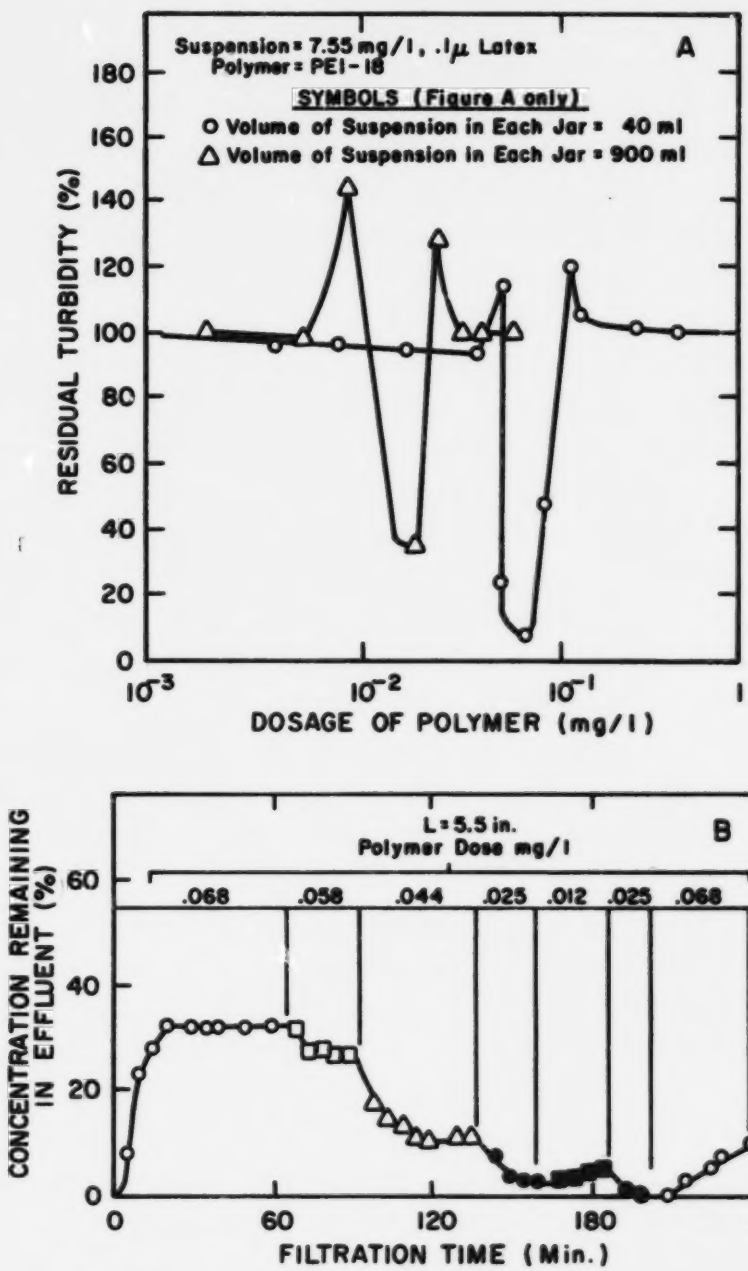

Figure 5. (A,B) Comparison of Jar Tests (A) and Pilot Filter (B) for Determining the Optimum Polymer Dose for Filtration.

in optimum dosages for coagulation and filtration can be observed if the jar tests are performed "correctly".

Some other investigators have also failed to observe an equality in the optimum polymer dosage for coagulation and filtration. For example, Mints (24) has written, "It should be pointed out that the minimum dose which ensures the required degree of clarification in filtration and the minimum dose for the formation of large quick falling flocs are not identical in most cases. The former is usually smaller than the latter and for the treatment of slightly turbid water may indeed be several times smaller". The discrepancy between Mints' observation and the results of this study can be due to the adsorption of polymer onto the surfaces of glassware utilized in conducting jar tests. The surfaces of glass (silica) beakers used in this research for the jar tests even when coated with chemicals such as Siliclad can compete with the colloidal particles in adsorbing the polymer added to the jar for particle destabilization. Only a fraction of the total amount of polymer added to a jar will be available to react with colloidal particles. The magnitude of this "available" fraction of polymer depends on the ratio of the surface area of the beaker in contact with the suspension to the surface area of the suspended particles in each beaker. The higher this ratio, the lower the fraction of polymer available for reaction with particles. This implies that the optimum polymer dosage determined by jar tests can be higher than the actual dosage necessary for optimum coagulation. This effect would be more pronounced for suspensions of low turbidity, where the total area of colloidal particles in the sample used for the jar test may have the same order of magnitude as the beaker area in contact with the suspension. The effect would also be pronounced if the polymer is adsorbed to a greater extent on the beaker surfaces than on the colloidal particles.

The Mechanism of Polymer Action in Filtration

To determine whether charge neutralization or (and) bridging is the dominant mechanism by which polyelectrolytes affect filter performance, the charges of the latex particles and the various polymers

used in this research were measured. The charges due to the emulsifier anion, the initiator, and the total charge (the sum of the emulsifier and initiator charges) for both .109 and 1.099 μ particles are presented in Table 3. The charges of various polymers at pH = 8.2 as determined by acid-base titrations are presented in Table 4. In the same table the optimum polymer dosages necessary for the coagulation and filtration of a 48 mg/l suspension of 1.099 μ latex particles are also shown. The optimum dosages of all polymers except PEI-6 are about equal. The charge per unit weight of polymers except PEI-6 are also almost equal. The optimum dosage for coagulation using a series of polyethylenimines has also been reported by Dixon et al. (25) to be independent of molecular weight above a certain minimum molecular weight. This analysis indicates that charge interactions play a significant role in the coagulation of latex particles by polyethylenimine.

The magnitude of the positive charge of the optimum dosages of PEI-18 and the negative charge of the latex particles for some of the experiments conducted in this research are compared in Table 3. Even if it is assumed that all of the polymer added to the system is adsorbed on the latex particles, the data indicate that optimum coagulation occurs and that particle restabilization commences before the negative charges associated with the latex particles can be completely neutralized by adsorbed cationic polymers.

To provide additional evidence, the electrophoretic mobilities of the latex particles were determined at several polymer dosages. The results are presented in Figs. 6 and 7. Here the residual turbidity of the supernatent in the jars and the mobility of the latex particles are plotted as a function of the polymer dosage added to the latex suspension. The data indicate that optimum particle destabilization occurs at negative mobility, confirming that complete charge neutralization is not required for effective coagulation. Furthermore, the data indicate that particle restabilization occurs before the charge on the latex particles has been reversed. This phenomenon has also been

TABLE 3

LATEX CHARGE AND THE OPTIMUM POLYMER DOSE

Particle Diameter (Microns)	Emulsifier Charge		Residual Charge		Total Charge		Ratio of Polymer Charge to Latex Charge at Optimum Dose
	$\mu coul/cm^2$	coul/gm	$\mu coul/cm^2$	$coul/gm^2$	$\mu coul/cm^2$	coul/gm	
0.109	7.96	4.16	1.53	0.802	9.49	4.96	0.5
1.099	46.4	2.40	3.24	0.168	49.64	2.57	0.2

TABLE 4

CHARGE OF POLYETHYLENIMINE AND OPTIMUM DOSE AT pH = 8.2

Polymer	Molecular Weight	Charge at pH = 8.2 (Coulomb/gm)	Optimum Dose (mg/ℓ) to Coagulate a Latex Suspension (1.1μ, 48 mg/ℓ)
PEI-6	600	9.3×10^2	0.050
PEI-12	1200	7.9×10^2	0.029
PEI-18	1800	7.6×10^2	0.032
PEI-600	40-60,000	7.4×10^2	0.024
PEI-1000	50-100,000		0.025

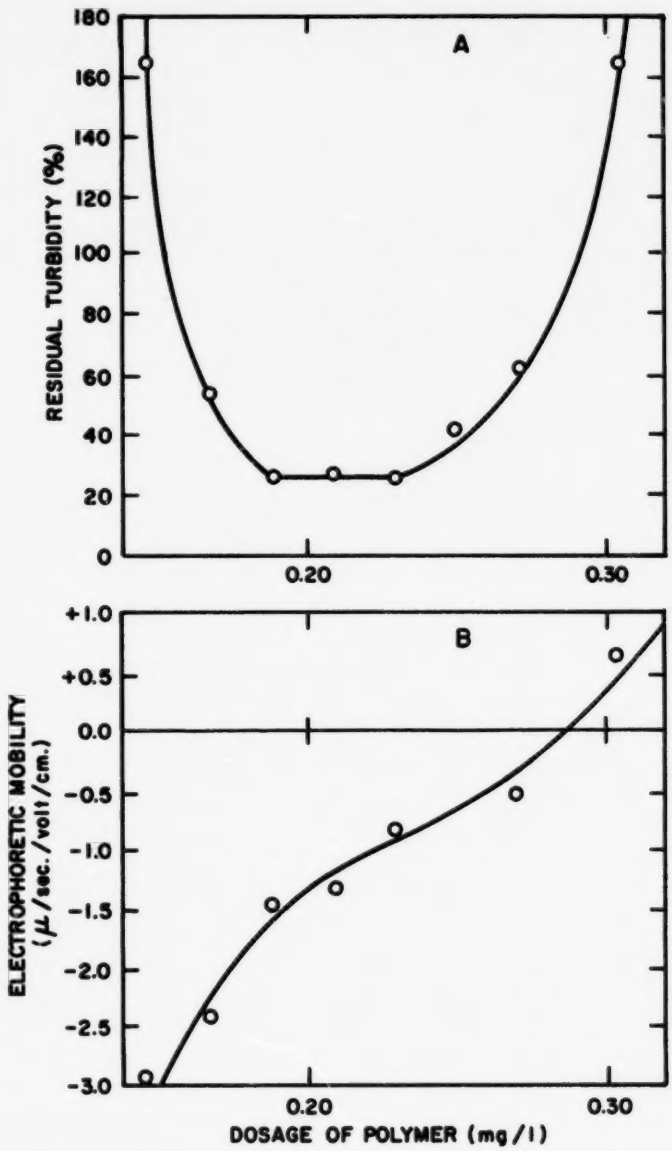

Figure 6. Effects of PEI-18 on Residual Turbidity (A) and Electrophoretic Mobility (B) of 0.109 μ Latex Suspension.

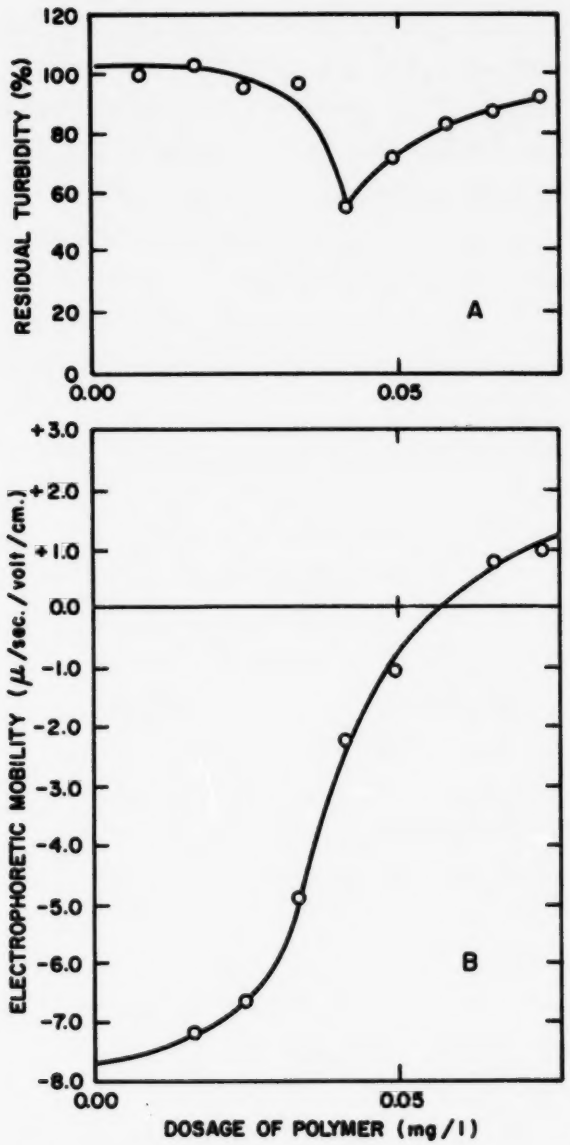

Figure 7. Effects of PEI-18 on Residual Turbidity (A) and Electrophoretic Mobility (B) of 1.099 μ Latex Suspension.

observed by many others in several coagulant-colloid systems (e.g., 26).

These findings indicate that charge neutralization is not the sole mechanism by which polyethylenimine destabilizes latex particles, since optimum coagulation did not occur at zero mobility. However, the close correlation between the optimum polymer dosages and the charge per unit weight of polymers (Table 4) suggests that the charge interactions are significant. These results are consistent with the following postulate. Segments of polymer molecules are adsorbed onto the surfaces of latex particles by electrostatic and chemical interactions between the positive sites of the polymer and the negative sites of the latex, while the remainder of the polymer molecules extend into the solution. These extended positively charged segments will be adsorbed onto the free negative sites of other particles when the particles are brought in close proximity. The polymer molecules provide bridges which enhance the attachment of the colloidal particles to each other.

It is generally accepted that the polymer molecule should have a rather large size (greater than the thickness of the diffuse layer) to act as a bridge in bringing about particle destabilization. However, it should be noted that the adsorption of the cationic polymers on negative colloids reduces the effective charge of the colloidal particles and therefore also reduces the thickness of the double layer surrounding such particles. It may also alter the van der Waals attractive forces. It is plausible that bridges can be formed even by low molecular weight polymers in such systems. Alternatively, steric effects can produce restabilization.

These conclusions are in accord with the findings of Dixon et al. (25) who studied the coagulation of silica suspensions by polyethylenimines, and Black et al. (27), who investigated the coagulation of clay suspensions with Cat-floc.

The high dosage of PEI-6 (Table 3) may be explained by considering that the low molecular weight polymer may not be completely adsorbed on the latex particles. Thus, the amount of PEI-6 which must be added to achieve a certain coverage of the latex surface can be greater than the corresponding value for larger polymers which are more completely

adsorbed. This is also in accordance with the findings of Dixon et al. (25).

Stoichiometry in Filtration

The results of experiments conducted to test for stoichiometry are presented in Fig. 8. The optimum dosage of the polymer (mg/l PEI-18) is plotted as a function of the concentration of suspended particles (mg/l). A linear relationship for both 0.1 and 1.1 μ particles is observed. Again, a similarity between filtration and coagulation is observed.

The data presented in Fig. 8 indicate that the optimum polymer dosages required for coagulating suspensions of different particle size but with equal concentration of particle surface are not equal. For the same weight concentration, a suspension of 0.1 μ latex spheres will have a surface concentration of (1.1/0.1) or 11 times that of a suspension of 1.1 μ latex spheres. However, a suspension of .1 μ latex particles would need only about one-half of the polymer which is necessary for optimum coagulation of a suspension of 1.1 μ latex particles at an identical particle surface concentration. This result is in disagreement with the findings of Black and Vilaret (28) who studied the coagulation of latex suspensions with Cat-floc. These investigators observed a linear relationship between the optimum polymer dosage and latex particle surface concentration, regardless of particle size. This latter finding seems questionable in view of the fact that the total charge per unit area of the latex particles increases markedly as particle size increases (Table 3). The same trend in the residual charge density of the latex particles has been demonstrated by Vanderhoff et al. (16). The discrepancy may be due to inaccuracies in determining the optimum polymer dosages in jar tests. Alternatively, Cat-floc may interact with and adsorb on the surface of the latex particles in a manner which is not primarily dependent upon electrostatic effects.

Molecular Weight of the Polymer and Filter Performance

The results of an experiment designed to evaluate the influence of molecular weight on the effectiveness of polymers as filter-aids are

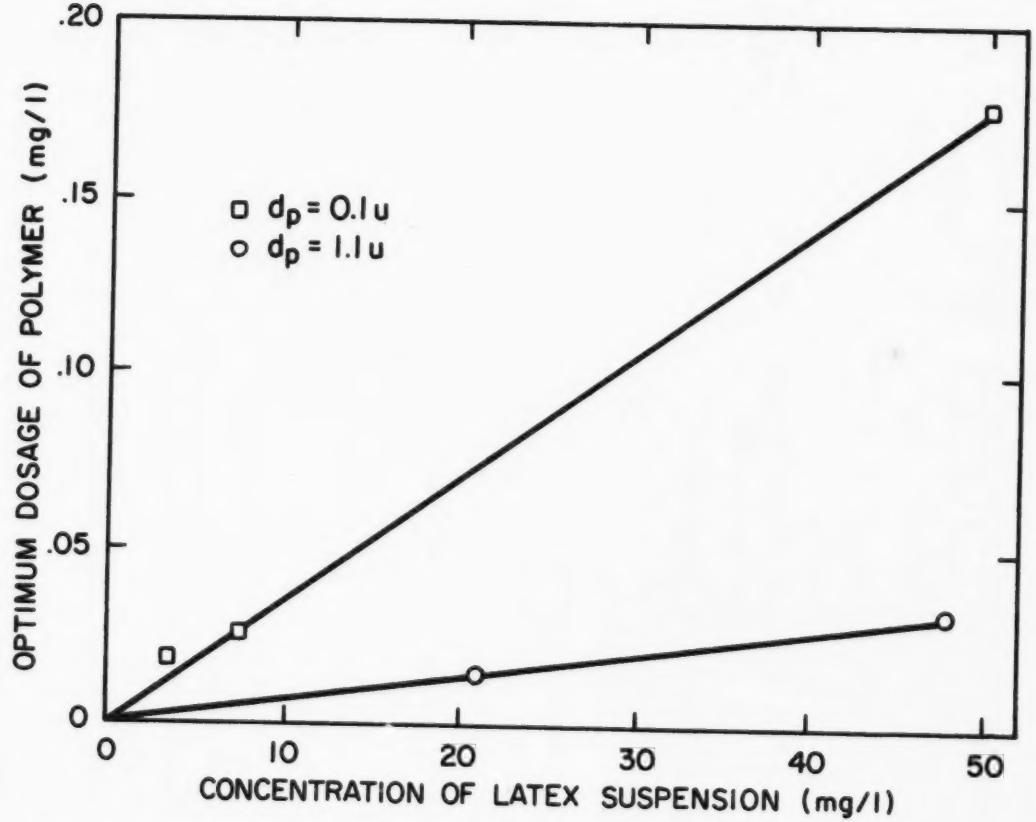

Figure 8. Stoichiometry in Filtration: Optimum Polymer Dosage (PEI-18) as a Function of Colloid Concentration.

presented in Figure 9. A suspension of 1.1 μ latex particles at a concentration of 48 mg/l was used as the filter influent. The optimum dosages of five homologs of polyethylenimine were determined by the pilot filtration technique (Table 4). Five shallow precoated filter beds (1.4 inch deep) were used, each of which received the latex suspension and one of the polyethylenimine homologs at the corresponding optimum dosage.

The removal efficiencies slightly increase as the molecular weight of the applied polymers increase, except for filter 3 (Fig. 9). A second experiment using only filter 3 produced results which are consistent with this observed slight increase in removal efficiency with increasing molecular weight. The results presented for filter 3 in Figure 9 were probably due to poor experimental technique, such as improper preparation of the stock polymer solution. The slight improvement in removal efficiency as the molecular weights of polymers increases is consistent with the head loss data and with visual observation of the filter beds. The rates of head loss development across the filters increase as the molecular weights of the applied polymers increase except for filter 3 (Fig. 9). The depth of significant particle penetration into the filter bed was observed to decrease with increasing polymer molecular weight. Particles were removed within a very thin top layer to the filter bed when PEI-1000 (molecular weight = 50-100,000) was used. At the other extreme, when PEI-6 (molecular weight = 600) was used, the particles penetrated into deeper layers. The particle penetrations into filter beds when using PEI-18 and PEI-600 which have intermediate molecular weights were observed to be between these two extremes. Based on these results it is concluded that when polymers of this type are applied at the optimum dosage in filtration, the efficiency of particle attachment increases as the molecular weight of the applied homolog of polymer is increased.

Suspensions of Low Particle Surface Concentration

The coagulation of suspensions containing low concentrations of suspended particles generally have been found to be quite difficult. Experimental results presented in Figure 10-A illustrate this problem.

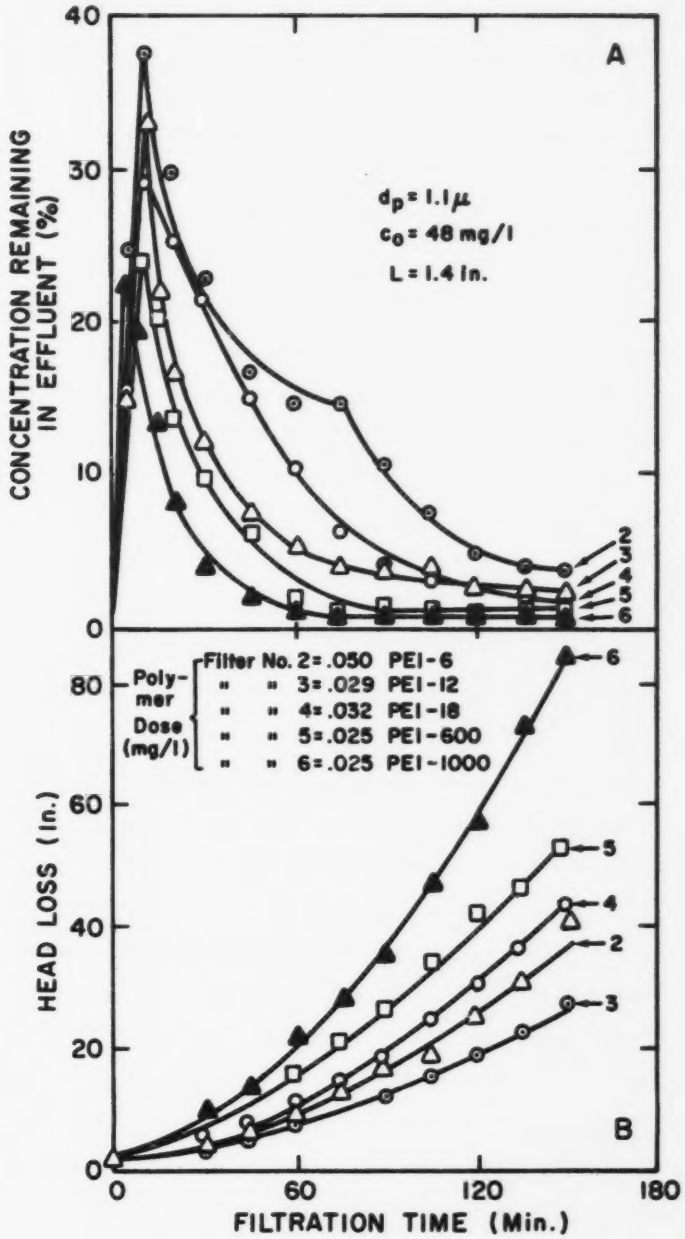

Figure 9. Effects of Molecular Weight of Polymer on Filter Performance at the Optimum Polymer Dosage.

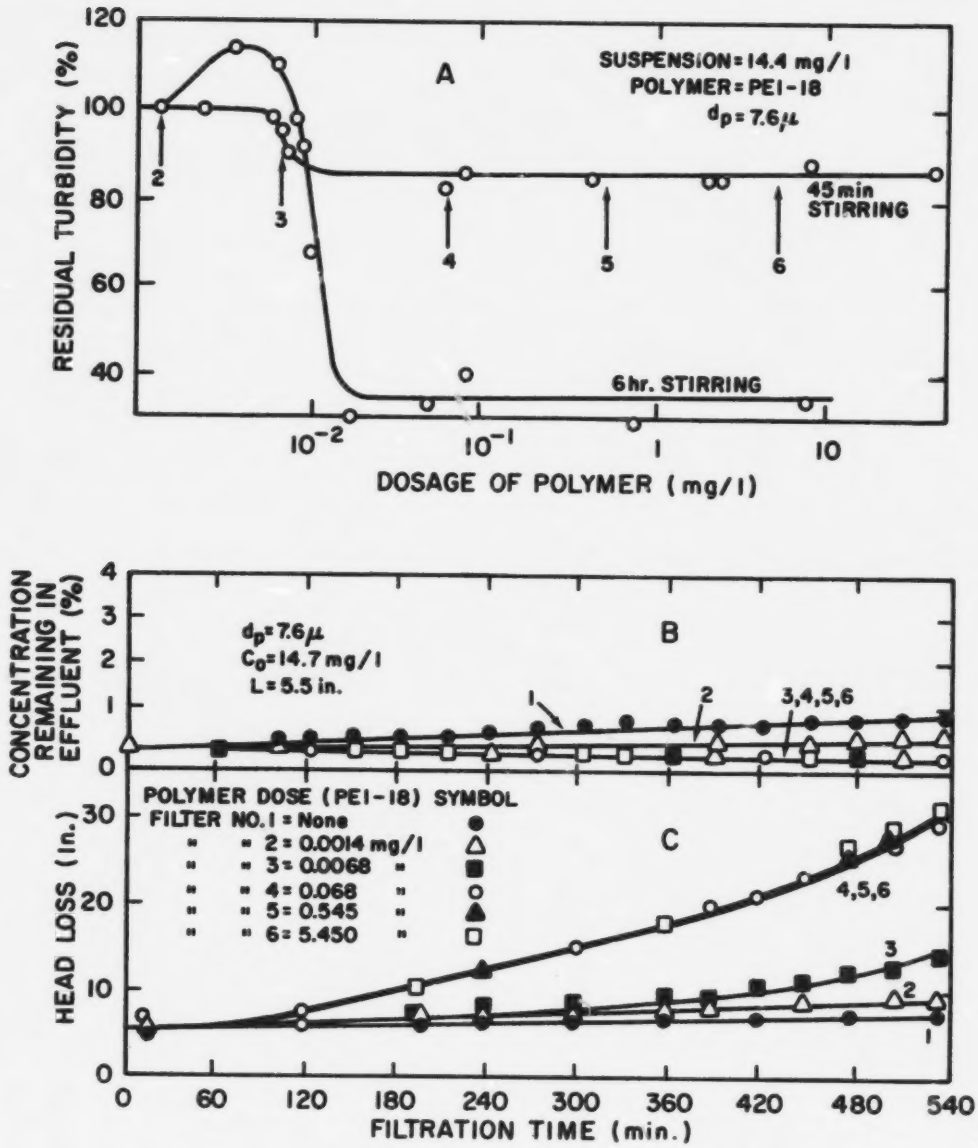

Figure 10. (A,B,C) – Effects of Polymer on Coagulation (A) and Filtration (B,C) of a low Turbidity Suspension.

Here a suspension of 7.6 μ latex particles at a concentration of 14.7 mg/l was treated with PEI-18. The coagulation of this water was quite slow. The suspension treated with the proper amount of the polymer required six hours of stirring before any significant coagulation could be observed. This problem arises from the low rate of interparticle contacts in this system; in other words, the process is limited by mass transport.

Data presented in Figures 10-B and 10-C, however, indicate clearly that such a suspension can be easily and effectively filtered. The data are consistent with the prediction of Yao's transport model for water filtration (3, 5) in which the transport efficiency is considered independent of the particle concentration. The efficiency of coagulation, however, depends markedly on particle concentration. Therefore, it is concluded that the direct filtration of waters containing low concentrations of particles, in contrast to their coagulation, is quite effective. This concept already has been put to practical use in the field by others (29).

It is useful to note that the filter which did not receive any polymer dosage except the precoat (filter 1) is as efficient as filter 4 which received the optimum polymer dosage, while the head loss across filter 1 was much smaller than that of filter 4 (Fig. 10-B, C). This indicates that when suspensions of low turbidity are filtered through a precoated filter bed, it may be profitable not to add any polymer to the filter influent until the capacity of the precoat is almost exhausted. This procedure would reduce the rate of head loss development and thus provide a longer filter run.

Suspended Particle Size and Filter Performance

Yao's theoretical and experimental studies showed that the size of the suspended particles affects the filter removal efficiency markedly (3, 4). To evaluate the validity of this prediction when polymeric filter-aids are continually added to the filter influent an experiment was conducted in which three suspensions of approximately equal concentration of .109, 1.099 and 7.6 μ latex particles were filtered through three shallow filter beds (depth = 0.8 inch). The results of these

filter runs are presented in Fig. 11. It is seen that the trend in removal efficiency as a function of particle size is in qualitative agreement with the prediction of Yao's transport study. The removal efficiency for filtering suspensions of .109 μ latex particles is rather high and remains high until the end of the experiment when all of the 85 inches of available head are exhausted. Filtration of the suspension of 1.099 μ latex particles is the least efficient and the breakthrough is observed at a head loss of 5 inches. Furthermore, filtration of 7.6 μ latex suspensions produces the best removal efficiency. Similar trends of filtration efficiency as a function of particle size have been observed in aerosol filtration (8, 30).

Tht head loss data (Fig. 11) show a remarkable dependence upon the size of the suspended particles. Analysis of the results of other experiments conducted in this research indicates a similar dependence of head loss on suspended particle size (6). Such analysis indicates that for any given amount of cumulative particle removal, the head losses across filters receiving suspensions of .1 μ latex particles at the optimum polymer dosages are much greater than the corresponding head losses when suspensions of 1.099 and 7.6 μ latex particles are filtered.

A plausible explanation for the dependence of head loss across a filter bed upon the size of the suspended particles is that suspended particles treated with the optimum polymer dosage have a tendency to be removed within the very top layer of the filter bed. This can cause the formation of a surface mat which is responsible for rapid head loss development. Under such circumstances the particle deposit (or the surface mat) acts as the filtering medium except for a very short period at the beginning of the filter run. A filter mat which is formed from suspended particles would show a resistance to flow which is an inverse function of the size of the suspended particles. The formation of a surface mat and the consequent rapid rate of head loss buildup is one of the main drawbacks of polymer-aided filtration. The prevention of surface mat formation has practical significance.

The formation of mats when filtering suspensions of .1 μ latex particles could not be prevented even at flow rates as high as 10 gpm/sq.

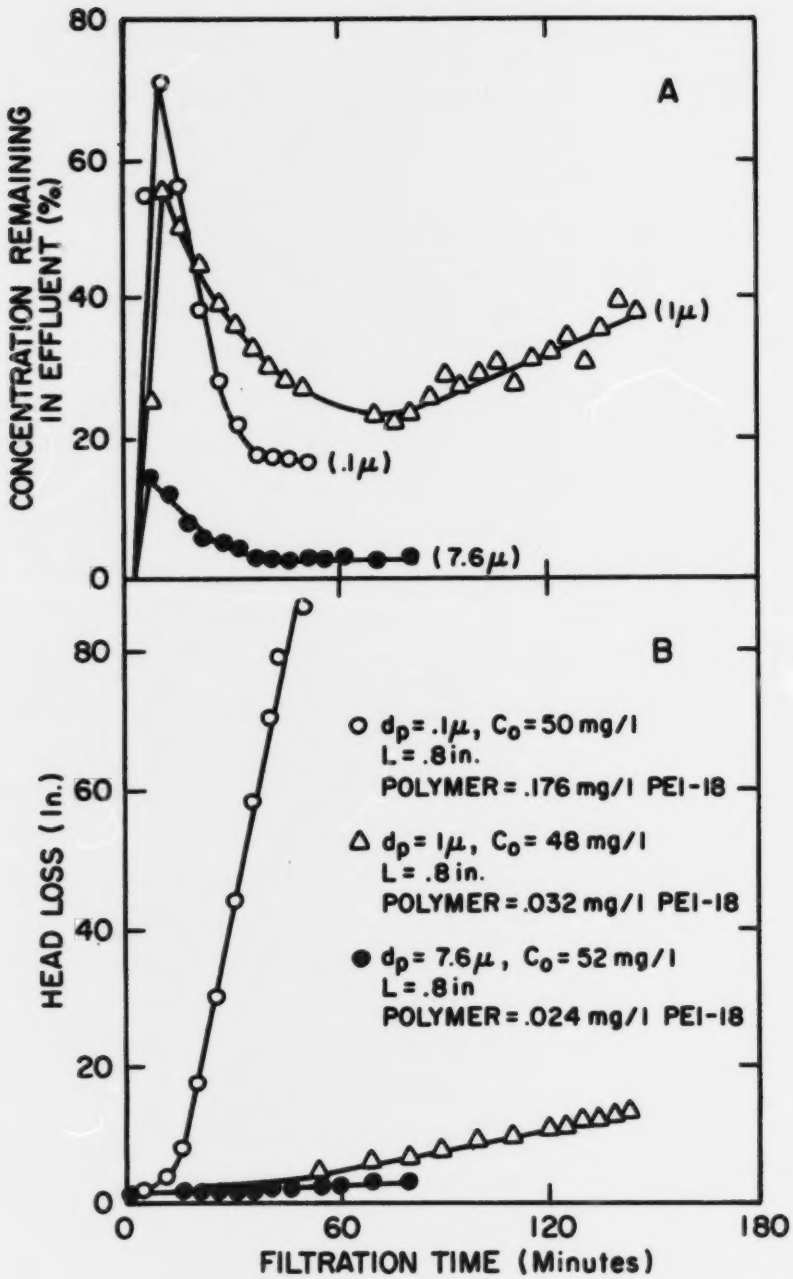

Figure 11. Effects of Suspended Particle Size on Filter Performance at the Optimum Polymer Dosage.

ft. The rate of head loss development was observed to be rapid and exponential while the removal efficiency remained quite high. In contrast, the use of larger filter grains was found to be effective in reducing or even eliminating the mat formation. Although this retardation of head loss build-up was associated with deterioration in removal efficiency, it seems plausible that efficient particle removal without excessive head-loss development can be obtained by use of deep filter beds of large grains even when suspensions of sub-micron particles are to be filtered. It is also plausible that a short period of flocculation to increase the size of sub-micron particles before reaching the filter can reduce the rate of head loss development.

Filtration of Trickling Filter Effluent

Laboratory Studies

Conventional wastewater treatment plants generally remove from 55 to 95% of the BOD and suspended matter from the raw wastewater. A major fraction of the remaining impurities is in colloidal form. Therefore, the knowledge obtained in this study regarding the filtration of colloidal suspensions should be, at least in principle, applicable to the further treatment of conventionally treated wastewater by filtration using polymeric filter aids.

Preliminary filter runs using trickling filter effluent without chemical pretreatment produced very low removals of turbidity using 0.8 mm glass beads in 5.5 inch deep filter beds. Results of the filtration of the effluent from the Mason Farm Wastewater Treatment Plant, Chapel Hill, N.C. using Prima-floc C-7 as a filter aid are presented in Fig. 12. In this experiment four filter beds (1, 3, 4 and 5) containing sand with a geometric mean diameter of 1.3 mm were precoated with a concentrated polymer solution; the depth of each filter bed was 5.5 inches. Filter 1 did not receive any additional polymer and served as a blank. Filter 4 received waste treated with the optimum polymer dosage determined from jar tests (14.2 mg/1). Filters 3 and 5 were underdosed (2.87 mg/1) and

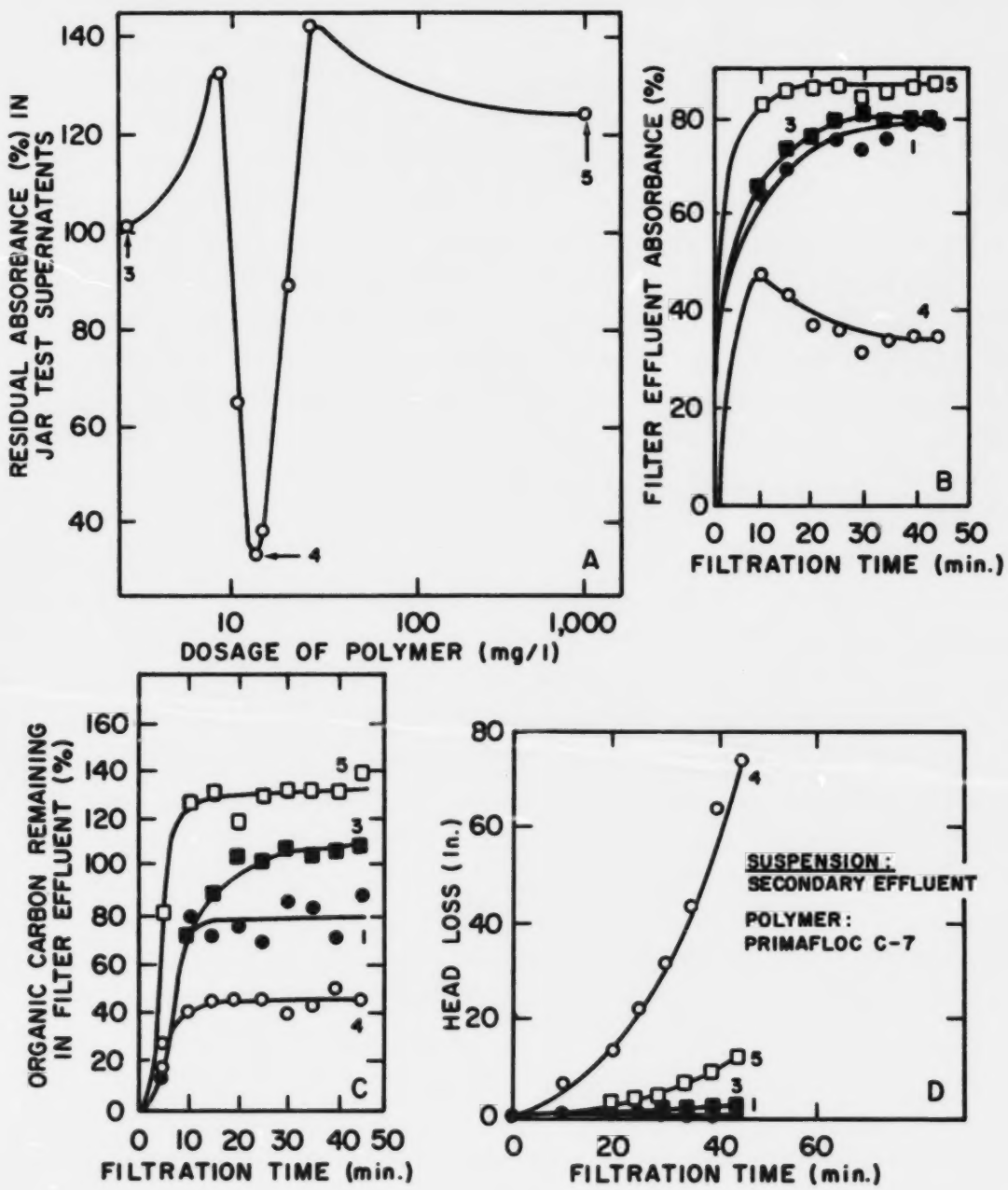

Figure 12. (A,B,C,D) - Effects of Polymer on Coagulation (A) and Filtration (B,C, D) of a Secondary Effluent from Mason Farm Wastewater Treatment Plant.

overdosed (71.2 mg/l), respectively. The similarity between the results of jar tests and filtration can be seen again from these results. Filter 1 which did not receive any polymer except the precoat showed a very low efficiency (about 20%) in terms of the removal of turbidity and total organic carbon. No significant head loss development across this filter was observed. The turbidity reduction achieved by filter 3 (the underdosed filter) and the corresponding head loss were very close to those of filter 1. The effluent of filter 3 does contain more organic carbon than the untreated wastewater influent. This may be due to organics in the polymer solution. A greater increase in TOC in the effluent of the overdosed filter (no. 5) was observed. The turbidity reduction achieved by this filter was also poor.

Filter 4 which received the optimum polymer dosage as determined from jar test data showed the best removal efficiency (about 60%) both in terms of turbidity and total organic carbon. It also had the highest rate of head loss increase.

Economic considerations can be a drawback for wastewater filtration. As can be inferred from Fig. 12, the optimum polymer dosage required for coagulation or filtration of the conventionally treated wastewater is rather high (14.2 mg/l in this case). At the present level of polymer cost (about $1 per pound) the application of Primafloc C-7 at a dosage of 15 mg/l would result in chemical costs of about 12 cents per thousand gallons of waste to be treated and so is not feasible at present. However, the number of polymers commercially available is numerous and it may be possible to find or develop a polymer which would be more acceptable.

The rapid increase in head loss is another drawback for polymer-aided filtration of conventionally-treated wastewater. It might seem that the removal of significant amounts of large particles could be responsible for this rapid head loss development by filling and blocking the pores in the bed. A comparison of results obtained by conducting jar tests on wastewater treatment plant effluent (Fig. 12-A) and on a suspension of 0.1 μ latex particles (Fig. 3-A) provided another plausible

explanation for, and perhaps a key to, the solution of this head loss problem.

As can be seen from Figs. 12-A and 3-A, in both cases an increase in residual absorbance is observed at polymer dosages surrounding the optimum polymer dosage. This phenomenon is due to the growth in the size of sub-micron particles (6). This comparison suggests that the majority of the colloidal impurities in trickling filter effluents are sub-micron in size. In this connection it is useful to note that the head loss development when suspensions of 0.1 micron latex particles were filtered was very rapid (Figure 3-C, 4-C). The similar rapid head loss build-up which was observed when the conventionally-treated wastewater was filtered can thus be attributed to the existence of sub-micron colloidal particles in wastewater treatment plant effluent.

Pilot Plant Studies

These experiments can be subdivided into three areas for discussion: (i) destabilization studies, (ii) filtration studies dealing with pretreatment, and (iii) filtration studies dealing with filter characteristics. Experimental results are presented and discussed in this perspective.

Destabilization Studies

Several anionic polymers were tested as primary coagulants using jar tests. The effects of calcium ions, pH, and flocculation period on the effectiveness of these polymers were also evaluated. Regardless of the combination of anionic polymer type and dosage, $[Ca^{2+}]$, pH, and flocculation period, effective coagulation was not observed.

Alum was investigated as a primary coagulant for trickling filter effluent. Results of a typical jar test are presented in Figure 13. Residual turbidity is plotted as a function of alum dose. Data obtained in another jar test for the removal of 5-day BOD, TOC, SS, and TP are presented in Figure 14. An optimum alum dose is observed (Figs. 13 and 14). In these and most other tests this optimum dose was found to be about 150 to 160 mg/l ($Al_2(SO_4)_3 \cdot 18H_2O$). Floc quality (size and settling characteristics) was especially poor in the underdosed and overdosed

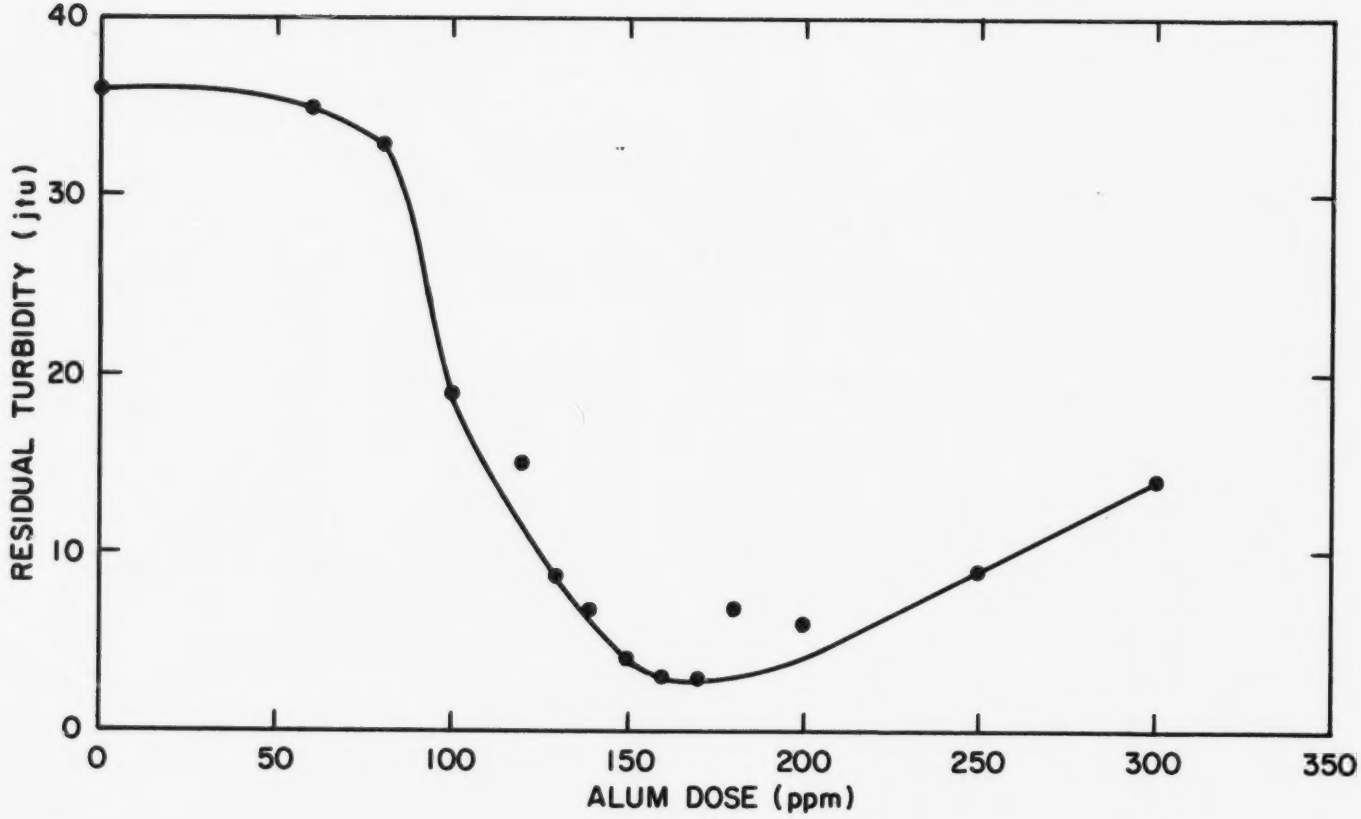

Figure 13. Effects of Alum on Coagulation of Secondary Effluent. Residual Turbidity vs. Alum Dose.

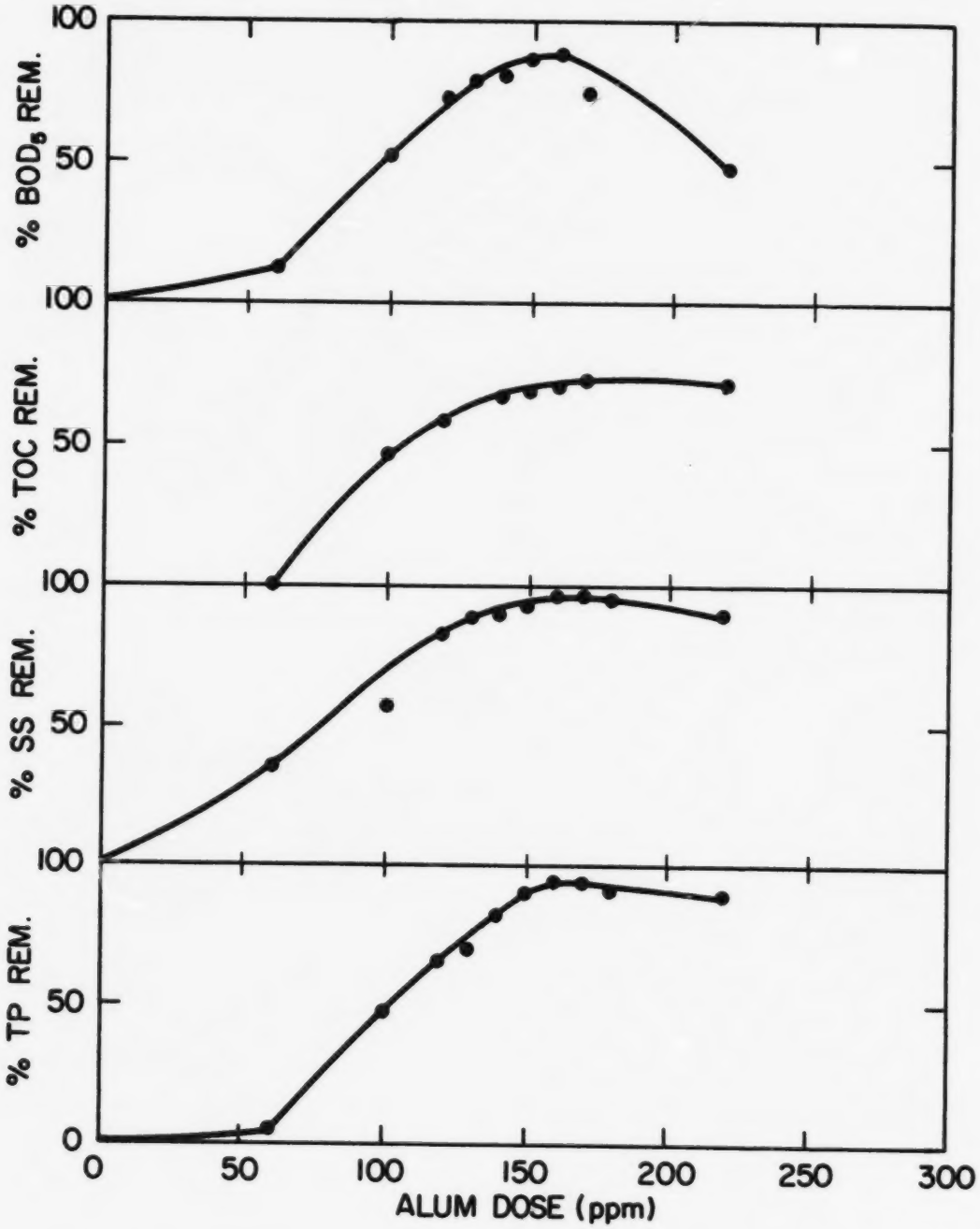

Figure 14. Effects of Alum on Coagulation of Secondary Effluent. Residual BOD_5, TOC, SS and TP vs. Alum Dose.

regions. Even at the optimum alum dose the floc did not settle well. Attempts to lower the optimum alum dose and to improve floc characteristics by changing the pH were unsuccessful.

Preliminary filter runs were made using the optimum alum dose. The flocs which were produced penetrated the filters very easily, and filter runs were terminated in an hour or less because of complete breakthrough. To improve the ability of the pilot filters to remove the alum-treated secondary effluent, it was decided to investigate the use of polymers as secondary coagulants. Again, jar tests were made to determine the types and dosages of polymers which had potential for filtration.

Results of jar tests using Purifloc A-23 as a secondary coagulant are presented in Figure 15. Residual turbidity is plotted as a function of polymer dose (mg/1, log scale). In these tests all jars received the optimum alum dose (in this case 150 mg/1). After two minutes of rapid stirring, the desired polymer dosage was added, after which the conventional jar test procedure was followed. Some slight improvements in residual turbidity were obtained. At a polymer dosage of 1 mg/1, turbidity was 1 jtu, SS were 1 mg/1, and TP was 0.4 mg/1. Most dramatic changes occurred in the appearance of the flocs. For polymer dosages between 0.5 and 20 mg/1, large and rapidly settling flocs were formed. Typical of polymer coagulation, regions of underdosing and overdosing were observed (Fig. 15). Based on these results, Purifloc A-23 was selected for further study in filtration tests.

Effects of Pretreatment on Filtration

Results of experiments using alum plus polymer are presented in Figures 16 to 19. Each figure contains results using a different media size. Residual turbidity (log scale to delineate differences) and head loss are plotted as functions of filtration time. Residual turbidity is expressed as the ratio of the filter effluent turbidity to the turbidity of the secondary effluent (per cent). Alum dose is constant (150 mg/1); polymer dosage was varied from filter to filter within a given run. Media size was varied from run to run; four sizes ranging from 1.65 mm to 4.08

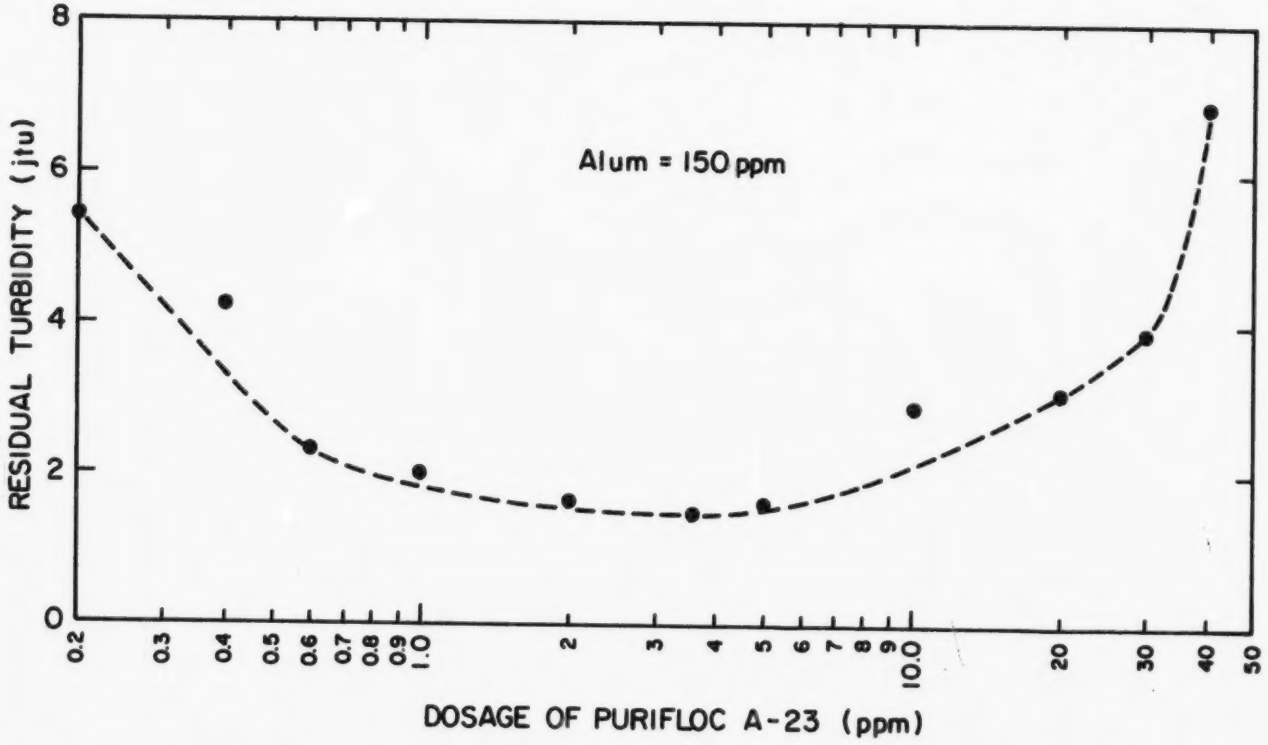

Figure 15. Effects of Purifloc A-23 on Coagulation of an Alum-treated Secondary Effluent. Residual Turbidity vs. Polymer Dose.

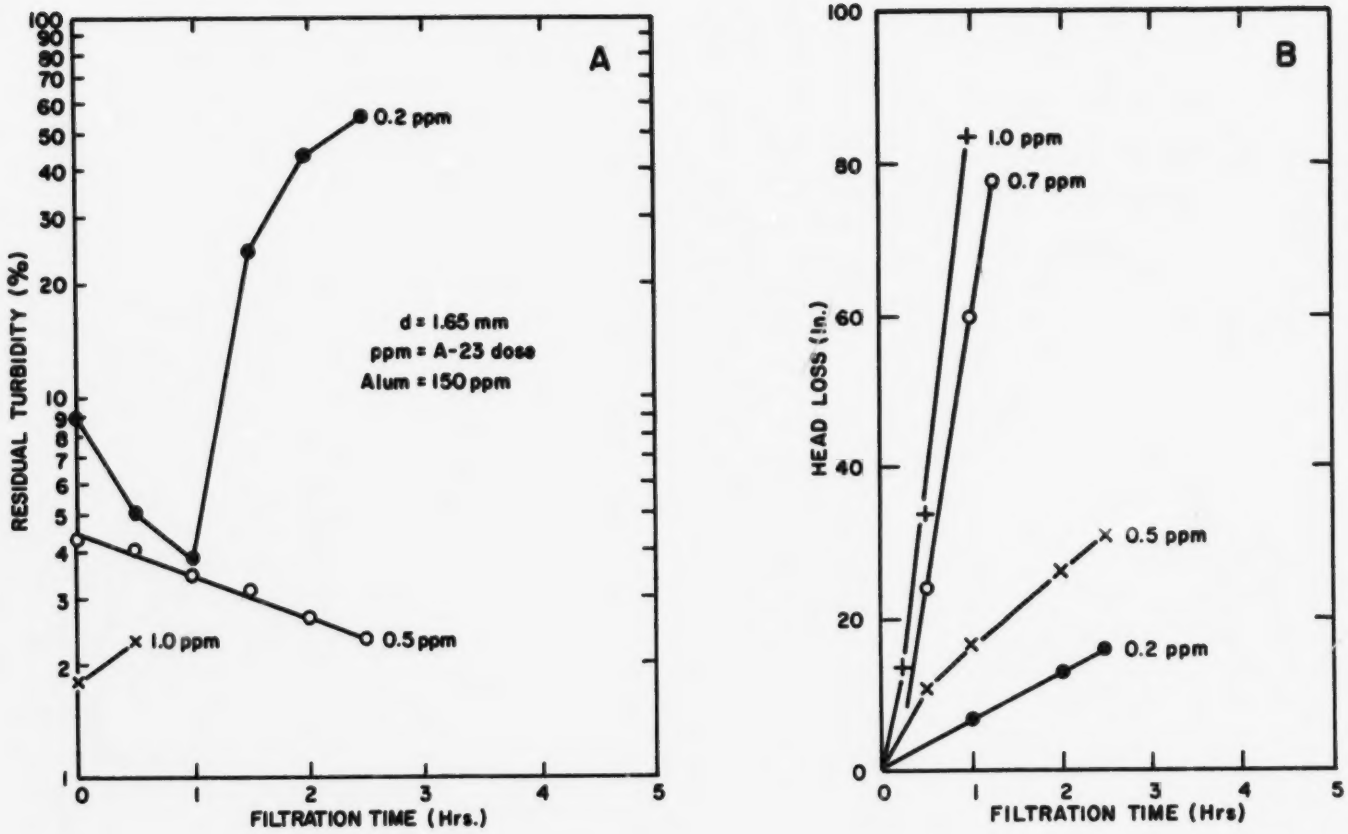

Figure 16. Effects of Purifloc A-23 on Filter Performance.

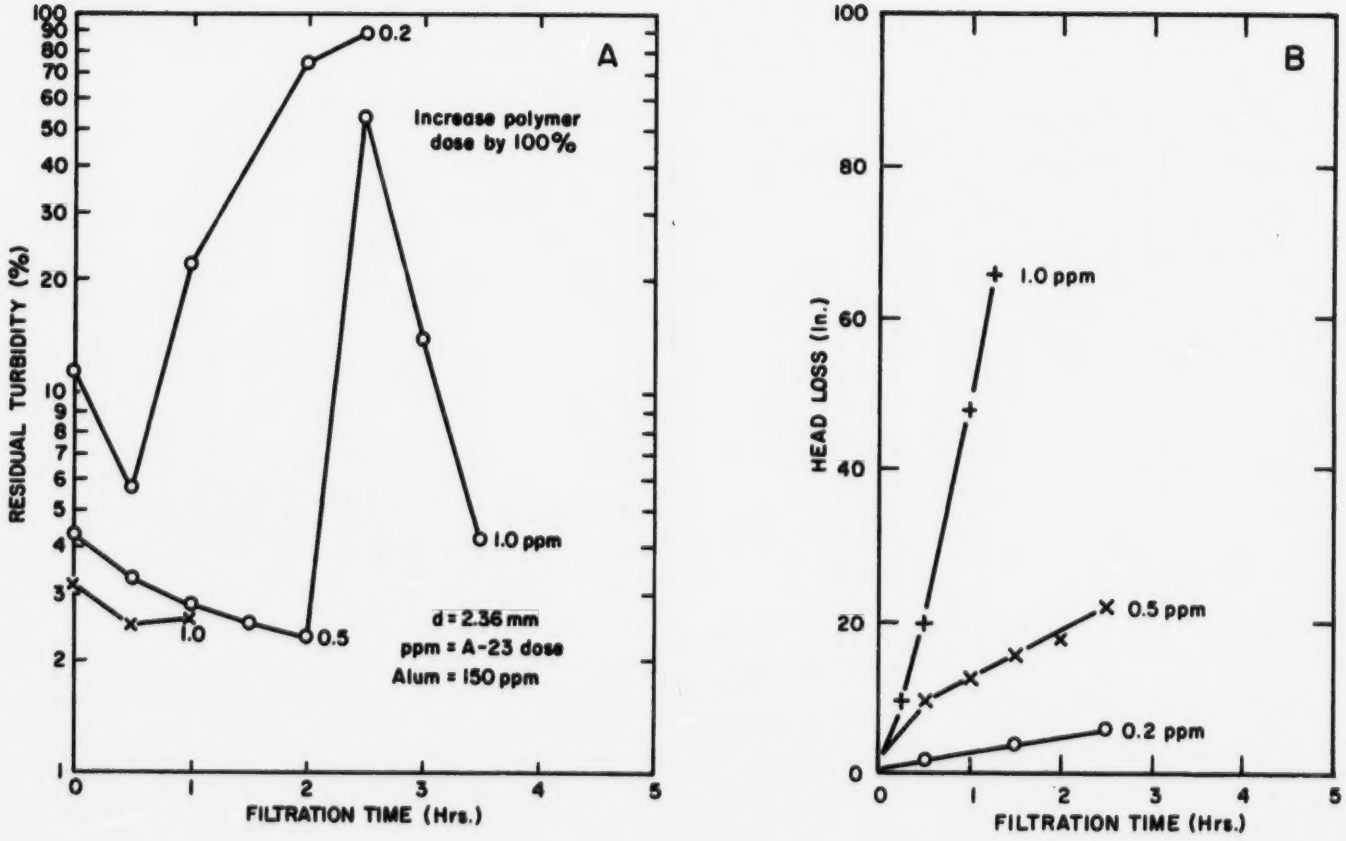

Figure 17. Effects of Purifloc A-23 on Filter Performance.

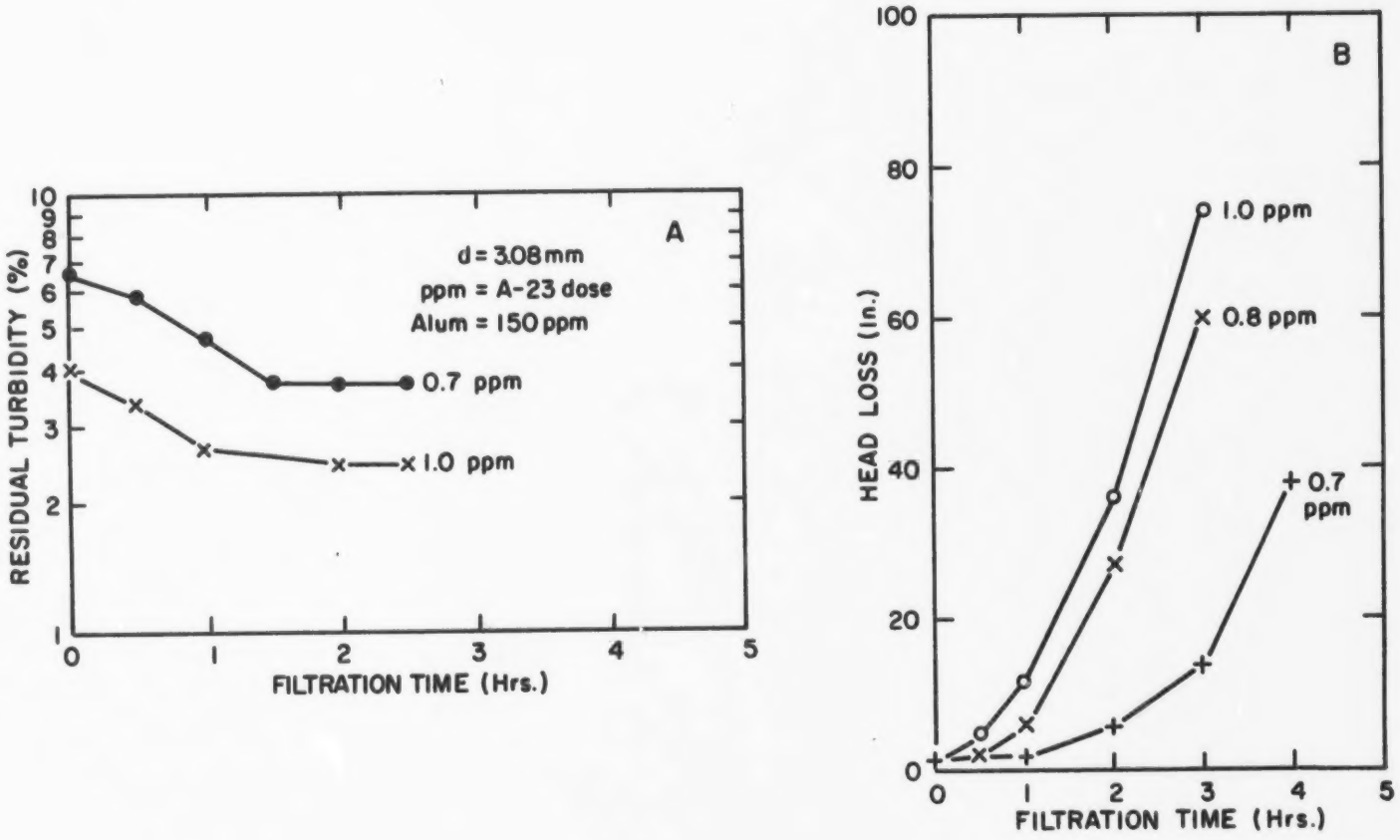

Figure 18. Effects of Purifloc A-23 on Filter Performance.

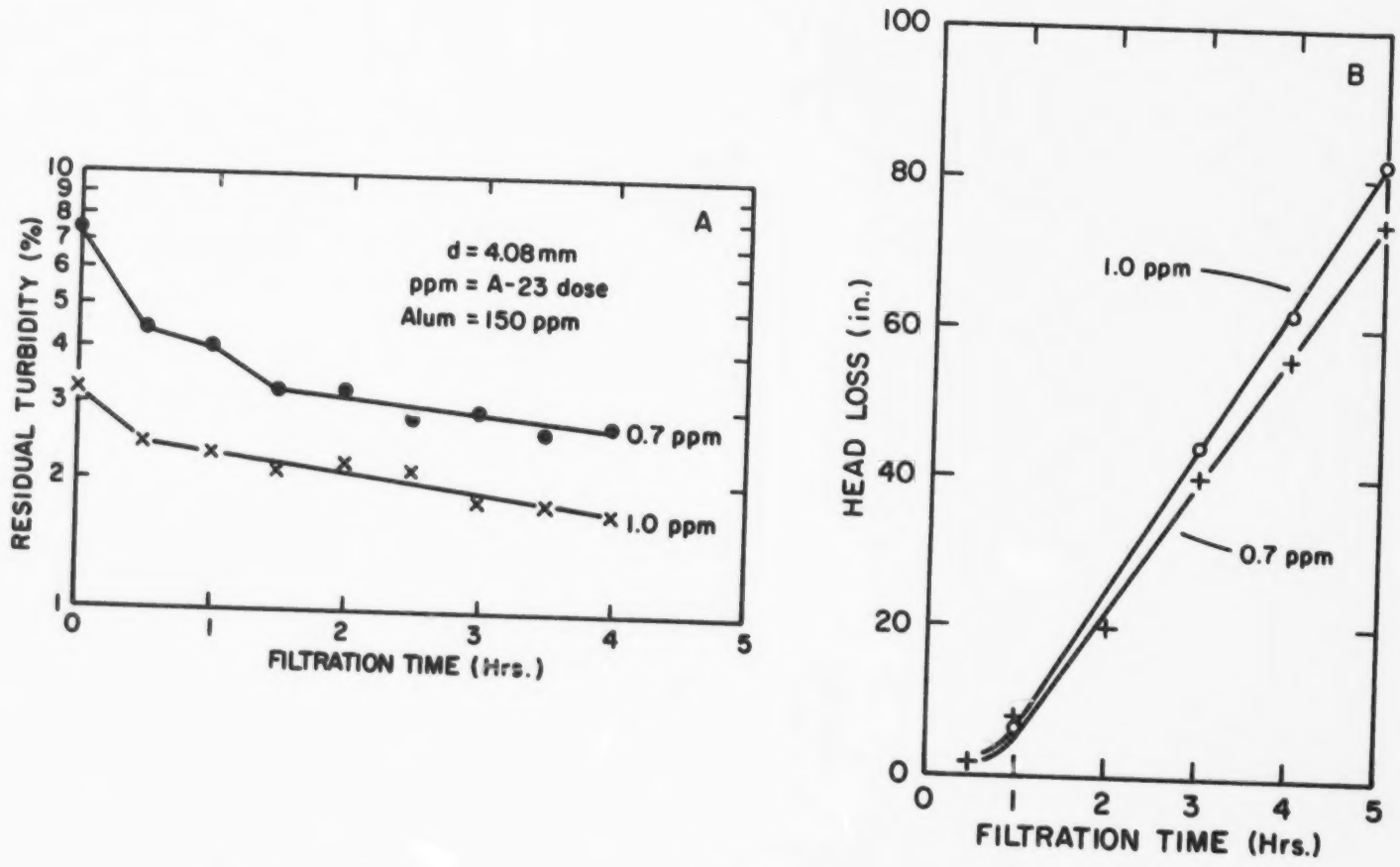

Figure 19. Effects of Purifloc A-23 on Filter Performance

mm were used.

Polymer applications ranged from underdosing up to the lower end of the optimum region for coagulation (Figure 15). Removal is observed to be dependent upon polymer dose while effects of media size on removal are slight (Figs. 16 to 19). In all cases a ripening period exists; filter efficiency improves at the start of a run, reaches a constant level and then, if sufficient time is provided, it deteriorates. The initial ripening period is probably due to less than complete attachment of the suspended particles to the media grains. After the initial deposit is accumulated, the attachment of newly applied particles to similar ones previously retained in the bed is more effective.

A simple experiment emphasizing the importance of the chemistry of the system is shown in Figure 17. One filter receiving a continuous polymer dosage of 0.5 mg/l broke through after 2.5 hours of operation. At that time 55 per cent of the turbidity of the secondary effluent was passing the filters. The applied polymer dose was then increased to 1.0 mg/l, in the optimum region of the jar tests. Within an hour the effluent turbidity fell to 14 per cent, and in another half hour was reduced to 4 per cent. At this time the available head loss was exhausted.

For these filter beds, the use of effective destabilization caused rapid and excessive head loss. The rate of head loss increase depended upon the polymer dosage. Unlike removal efficiency, however, the rate of head loss is also very dependent upon media size. Larger media produce lower rates of head loss increase while having only minor effects on effluent quality. To investigate further the trade-offs between pretreatment and filter characteristics, a series of experiments using several media sizes was conducted.

Effects of Filter Characteristics

The results of experiments in which media size was varied are summarized in Figure 20. Head loss is plotted as a function of filtration time for seven sizes of filter media. The optimum alum dose for runs using 1.65, 2.36, 3.08, and 4.08 mm media was 150 mg/l. The optimum alum dose for a second run with 4.08 mm media and also for filters using

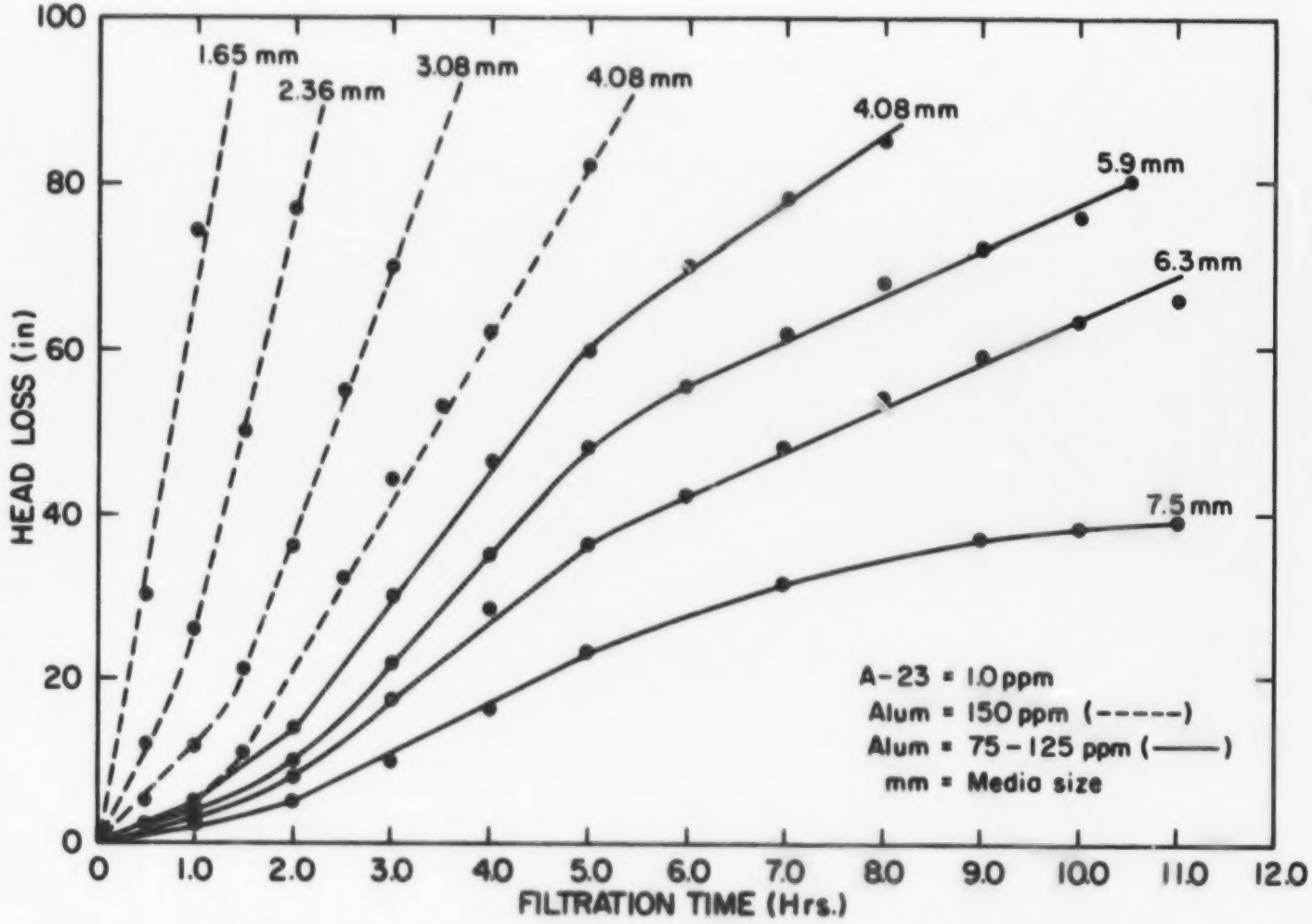

Figure 20. Effects of Media Size on Filter Performance. Head Loss vs. Filtration Time.

5.9, 6.3, and 7.5 mm media varied from 75 to 125 mg/l during the course of the run. For all experiments a polymer dosage of 1.0 mg/l Purifloc A-23 was used. As expected, the head loss increase during filtration decreases with increasing media size. Differences between the two runs using 4.08 mm are ascribed to the different alum dosages required. These head loss data will be discussed in a different perspective subsequently. Here one can note that filters using small media (1.65 mm is this case) will have their runs terminated due to utilization of available head, while filters using larger media (7.5 mm in this case) may have their runs terminated because of poor effluent quality.

The residual turbidity (jtu, log scale) observed in these experiments is plotted as a function of filtration time in Figure 21. In this case removal is only moderately dependent upon media size. In all cases a ripening period occurs. The upset after 5 hours for the 7.5 mm bed is probably due to an increase in the alum dose from 75 to 125 mg/l at that time. An increase in the polymer dose after 10 hours provided immediate improvement, probably because the 1.0 mg/l dose of Purifloc A-23 is at the low end of the optimum region (Fig. 15). These data are considered again in a different perspective in the following discussion.

Procedures for Filter Design

Filter design involves consideration of the quantity and quality of water produced, and of the costs of this production. Conventionally, rather standardized filters are specified (e.g., filtration rate = 2 gpm/sq ft, bed depth = 24 inches, media size = 0.6 mm, available head loss = 8 feet). The operator is then required to produce a desired quantity and quality of finished water by adjusting the pretreatment of the water prior to filtration. Effective destabilization in pretreatment can reduce water production by shortening filter runs through rapid head loss buildup, while poor destabilization can impair water quality and hence reduce water production by the breakthrough of solids in the filter effluent. In most cases an optimal (least sort) combination of pretreatment and filter costs to produce a desired effluent quality is not obtained, or even sought.

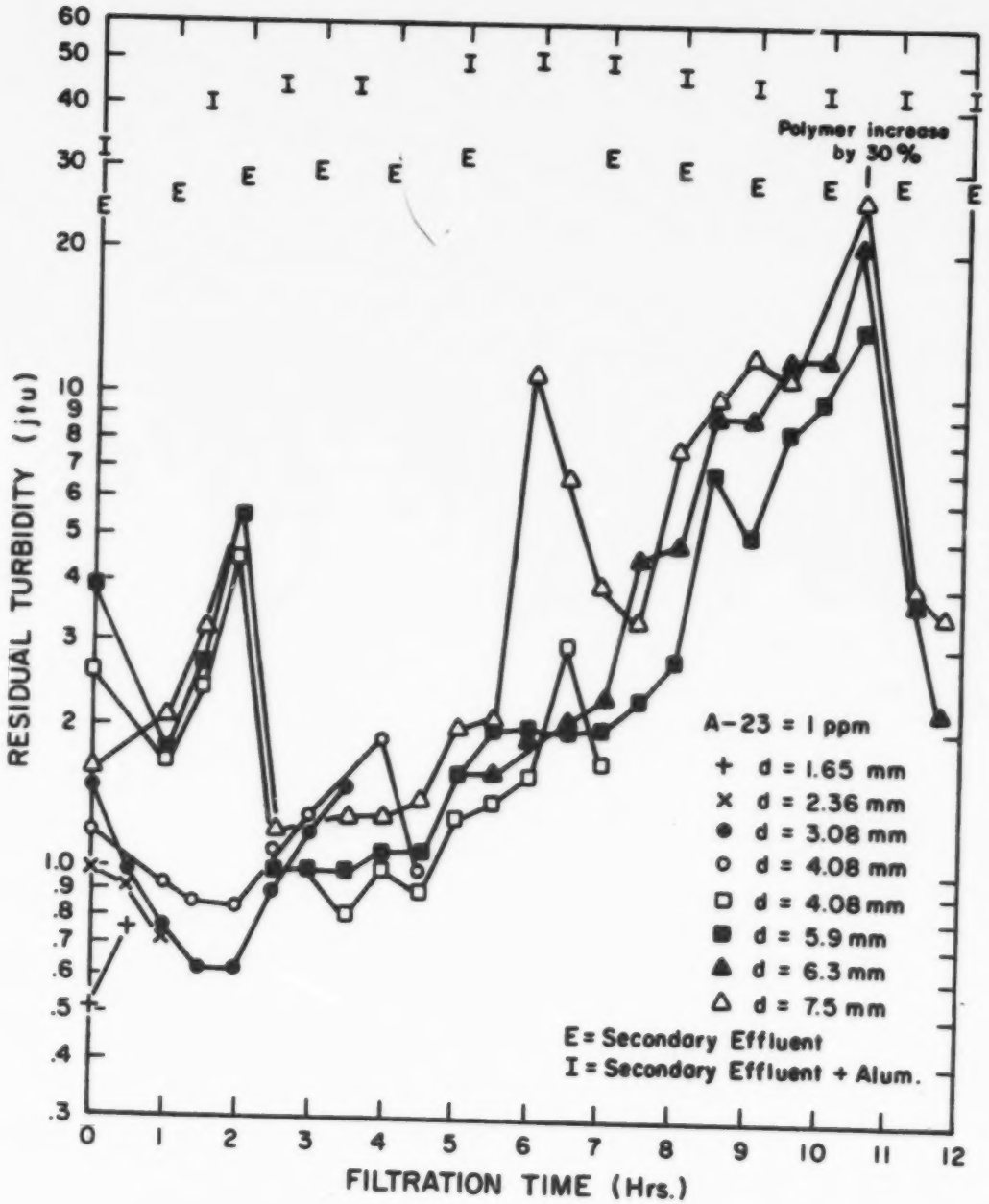
RESIDUAL TURBIDITY (jtu)
FILTRATION TIME (Hrs.)
Polymer increase by 30 %
A-23 = 1 ppm
d = 1.65 mm
d = 2.36 mm
d = 3.08 mm
d = 4.08 mm
d = 4.08 mm
d = 5.9 mm
d = 6.3 mm
d = 7.5 mm
E = Secondary Effluent
I = Secondary Effluent + Alum.

Figure 21. Effects of Media Size on Filter Performance. Residual Turbidity vs. Filtration Time.

Now destabilization in pretreatment is difficult to vary gradually. Coagulants tend to either work or not work. In contrast, particle transport in filter beds can be varied continuously over a wide range by changes in filtration rate and media size. Conventional filter design specifies what is easy to vary (particle transport), and leaves unresolved what is difficult to control (particle destabilization). It is useful here to consider a reversal of this procedure--one could specify an effective destabilization procedure and then design a filter to produce a desired quantity and quality of water using this pretreatment. By considering several pretreatment procedures (together with their associated filter designs), the least cost combination of filter and pretreatment costs could be selected. To implement this approach, experiments are needed. The data obtained in this research will be used to illustrate this approach.

Length of filter run is plotted as a function of media size in Figure 22. Pretreatment consisted of 150 mg/l of alum followed by 1.0 mg/l of Purifloc A-23. The filtration rate was 2 gpm/sq. ft. Filter runs were terminated because the available head loss (80 inches) was exceeded, or because the effluent quality exceeded 10 jtu. An optimum media size of about 5 mm exists for this pretreatment condition (Fig. 22). For smaller media, the runs were terminated because of head loss buildup; for larger media the runs were terminated because of poor effluent quality. The maximum length of run was 11 hours, corresponding to 1320 gals/sq. ft. of filter area.

Based on these results the following experimental procedure is suggested for consideration in filter design:

1. Select a suitable pretreatment procedure using jar tests. Determine a desirable type and concentration of destabilizing chemical, or a combination of chemicals.
2. Using this pretreatment procedure, evaluate the effects of media size using pilot filters at a constant filtration rate. If desired, consider dual and multimedia beds, biflow filtration, etc.
3. Repeat (2) using other filtration rates.

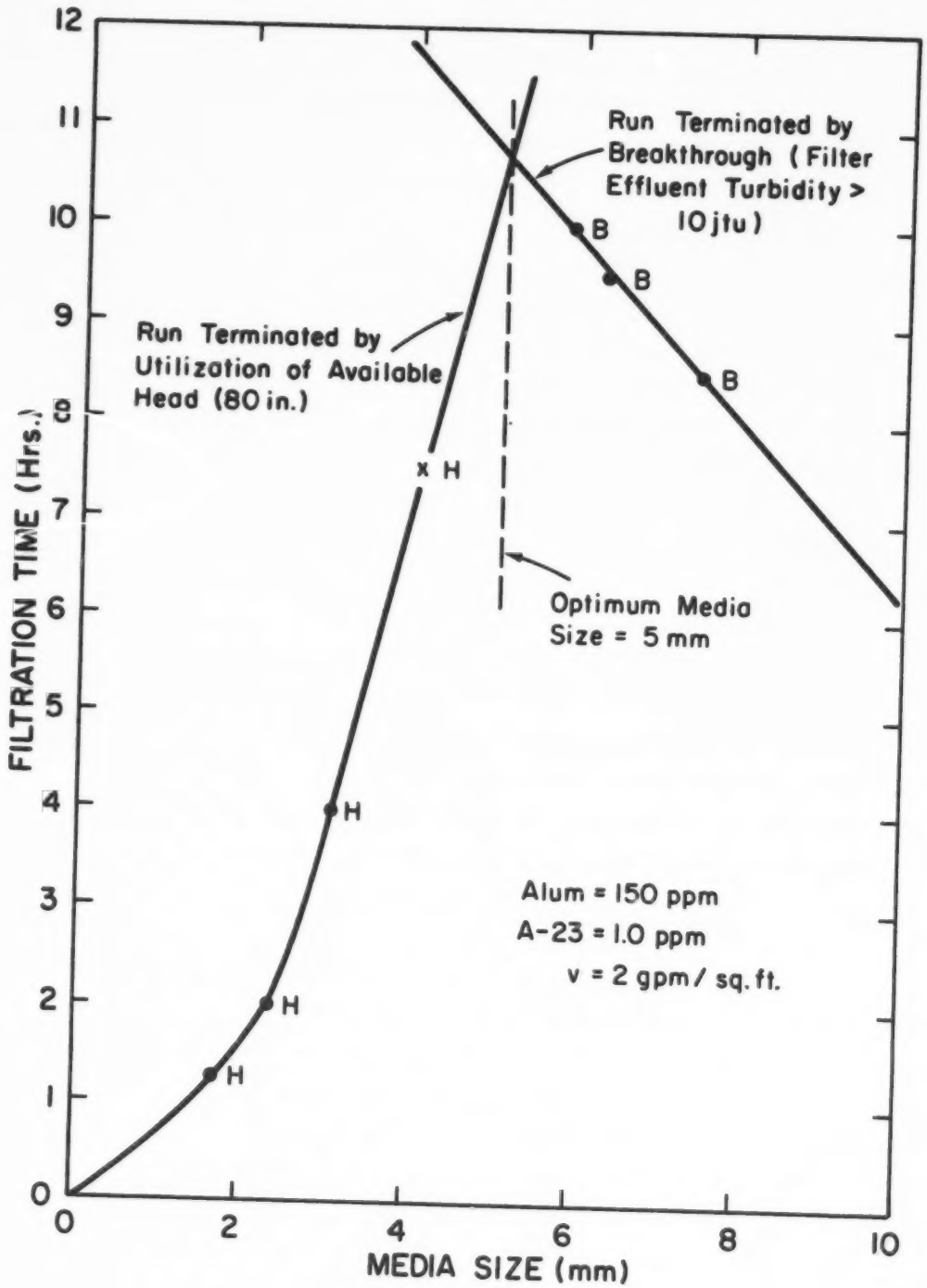
FILTRATION TIME (Hrs.)
MEDIA SIZE (mm)
Run Terminated by Breakthrough (Filter Effluent Turbidity > 10 jtu)
Run Terminated by Utilization of Available Head (80 in.)
Optimum Media Size = 5 mm
Alum = 150 ppm
A-23 = 1.0 ppm
v = 2 gpm / sq. ft.
B
H
x H

Figure 22. Determination of Optimum Media Size.

4. Considering the results of (2) and (3), select the combination of media size and filtration rate that provides maximum filtered water production given constraints of available head and desired effluent quality.
5. If desired, use the results of (2) and (3) to determine the effects of design head and effluent criteria on the costs of the process.
6. Design suitable backwash facilities. For larger media this can require air wash.
7. Repeat steps (1) through (6) for other suitable pretreatment procedures.
8. Compare the costs of each combination of pretreatment, filter, and backwashing system. Select the final design, considering also such factors as variability in raw water quality.

This general approach requires experimentation for design, and is more time-consuming and expensive for the design engineer. It adds experimentation at the pilot plant level prior to design, in order to reduce experimentation at the full-scale plant level after design and construction. It shifts some of the responsibility for pretreatment from the operator to the designer. It may also provide for more effective operation by selecting a pretreatment process that will be effective in destabilization (recall that destabilization is hard to control) and providing a filter that is tailored to this pretreatment (recall that particle transport is more readily controlled).

Filtration of Calcium Phosphate Suspensions

Coagulation Studies

Jar tests were conducted to determine the feasibility of using polymers as filter aids in the direct filtration of suspensions of calcium phosphate precipitates. Results of experiments using a cationic polymer (Cat-floc) are presented in Figure 23. Residual phosphorus (per cent) is plotted as a function of polymer dosage (mg/l, log scale). Phosphorus concentrations present in the supernatent after settling (3.11 mg P/l) or in the filtrate after settling and membrane filtration (2.71 mg P/l)

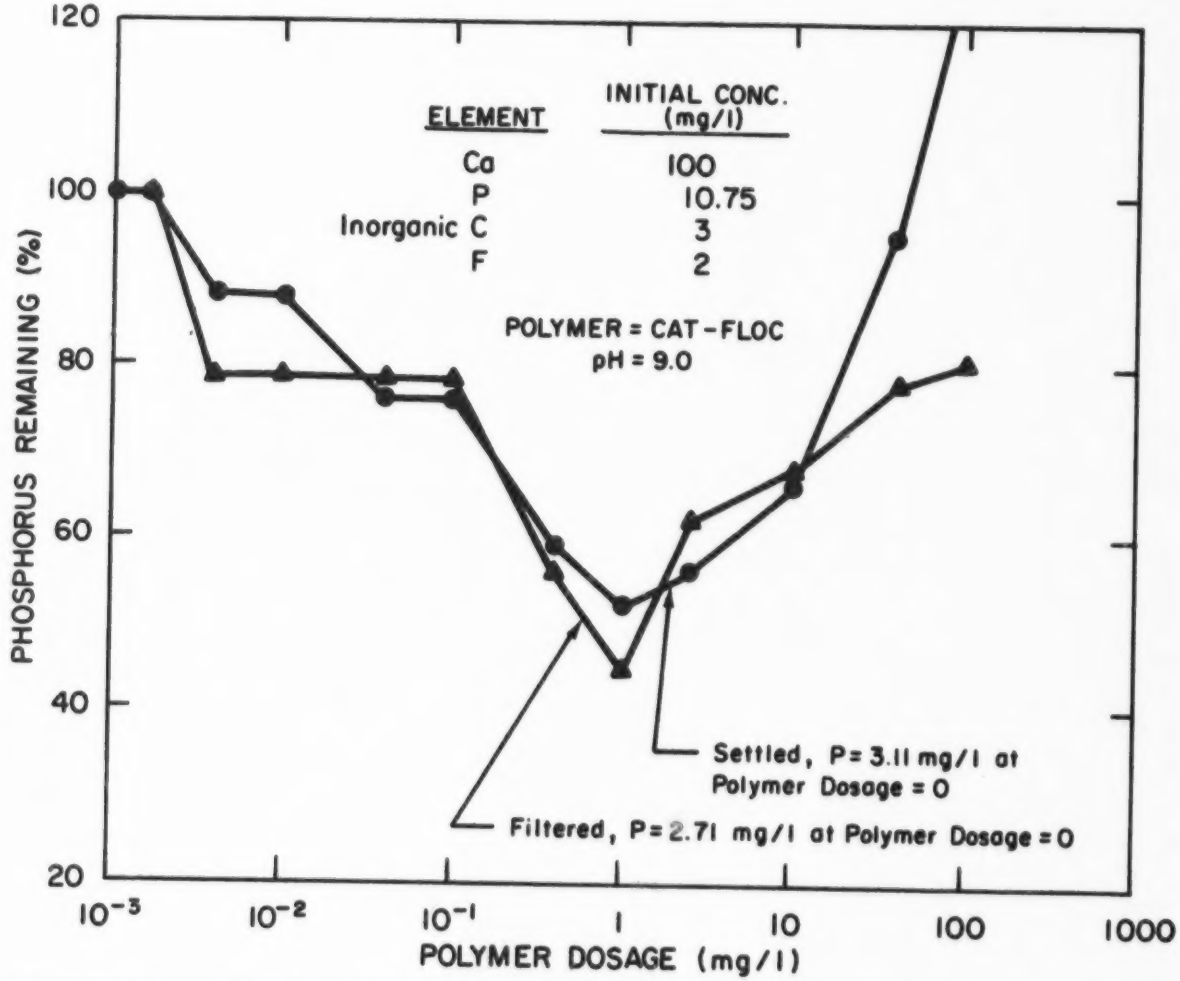

Figure 23. Effects of Cat-Floc on the Coagulation of Calcium Phosphate.

when no polymer was added have been used to calculate the percentages of residual phosphorus, rather than the initial phosphorus in the jars at the start of the test (10.75 mg P/1).

The optimum polymer dosage, defined here as the dosage which produces the minimum residual phosphate, is about 1 mg/1. The minimum concentrations of phosphorus are 1.59 mg P/1 (after settling), and 1.19 mg P/1 (after membrane filtration). Both underdosing and overdosing occur. A rather broad optimum region is observed, suggesting that the process could be easily controlled in a continuous-flow system.

Prima-floc C-7 (a cationic polymer) and Purifloc A-23 (an anionic polymer) were tested and produced effective destabilization in jar tests, with results similar to those presented in Figure 23 (32). Cat-floc was selected for further evaluation in direct filtration tests using laboratory filters (Figure 1).

Filtration Tests

The results of a typical filtration experiment are presented in Figure 24A and B. Residual phosphorus (per cent) is plotted as a function of filtration time (hours) in Figure 24A. Filter 1 received no polymer and hence was "underdosed"; filter 4 received a continuous dosage of 1 mg/1 of Cat-floc, the optimum dosage. Filters 5 and 6 received 10 and 100 mg/1 of Cat-floc and hence were overdosed (see Figure 23). All filter beds were precoated with a Cat-floc solution. Removal efficiency is filter 4 > filter 5 > filter 6 > filter 1. Head loss (inches) is plotted versus filtration time (hours) in Figure 24B. The rate of head loss increase is filter 4 > filter 5 > filter 6 > filter 1.

Filter 4 received the optimum polymer dosage, produced the best effluent, and exhibited the greatest head loss. Over 90 per cent removal of phosphorus was achieved after 3 hours without prior sedimentation. Underdosed and overdosed filters were much less effective. It can be concluded that an optimum polymer dosage for the filtration of calcium phosphate suspensions does exist, and that polymer underdosing and overdosing also occur. While not evaluated experimentally, stoichiometry is presumed to occur. The role of particle destabilization in the

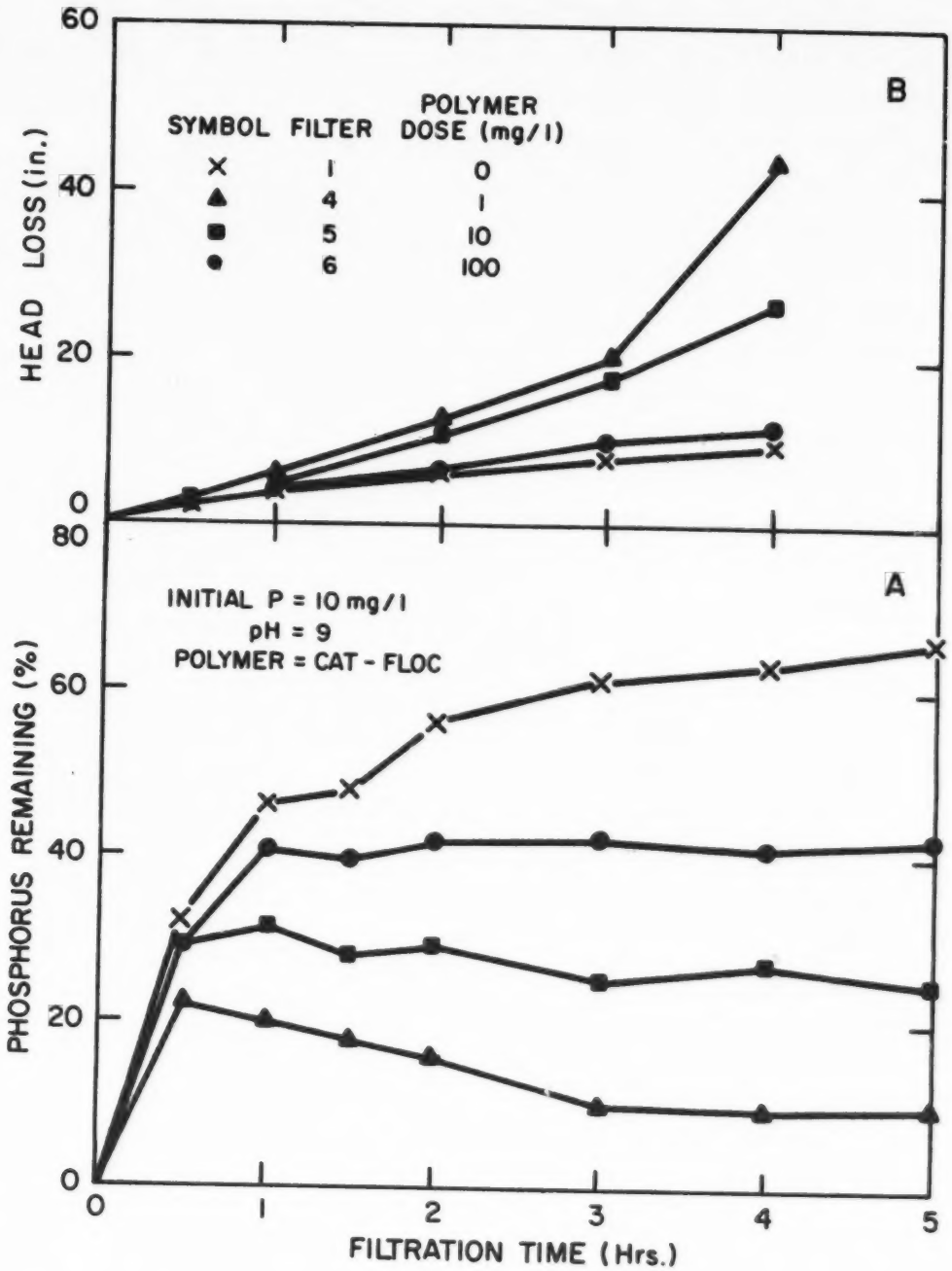

Figure 24. Effects of Cat-Floc on the Filtration of Calcium Phosphate.

filtration of these suspensions is demonstrated. The coagulation and filtration of these materials are analogous. Jar tests may be used to evaluate the effectiveness of polymers as filter aids.

Development of Filtration--A Theoretical Perspective

Consider first the efficiencies of particle aggregation in coagulation and particle removal in filtration. Coagulation efficiency may be related to the dimensionless product $\alpha_C \phi G t$, where α_C is a collision efficiency factor that reflects the chemistry of the system, ϕ is the volume of solid material (colloidal and suspended particles) per unit volume of suspension, G is the mean velocity gradient which reflects the rate at which contacts occur between particles by mass transport, and t is the detention time in the flocculation tank (33). In a similar way the efficiency of particle removal in filtration may be described by a dimensionless product $\alpha_F(1-f)\eta(L/d)$, where α_F is a collision efficiency factor that reflects the chemistry of the system, (1-f) represents the volume of filter media per unit volume of filter bed (f = porosity), η is a "single collector efficiency" that reflects the rate at which particle contacts occur between suspended particles and the filter bed by mass transport, and L/d, the ratio of bed depth to media diameter, represents the number of single collectors in the system and is somewhat analogous to detention time in coagulation processes. The single collector efficiency is an inverse function of media size, filtration rate, and water temperature, and also depends upon the size and density of the particles to be filtered (5).

The development of packed-bed filtration processes in water and wastewater treatment is presented in Table 5 in terms of the dimensionless product $\alpha_F \eta(L/d)$. For the purposes of this development the differences in bed porosity among the processes are small and have insignificant effects. Let us begin by considering infiltration galleries, where surface waters are filtered through porous strata prior to withdrawal by wells. Similar phenomena occur in ground water recharge with treated wastewater. No destabilization is attempted in these processes, and the suspended

TABLE 5

DEVELOPMENT OF FILTRATION PROCESSES

Filtration Process	Destabilization	Stability Factor * (α_F)	L / d (L/d)	v / d / η**	$\alpha_F \eta (L/d)$
Infiltration Gallery, Ground Water Recharge	None	10^{-5}	L≃100 ft d≃0.2mm (L/d)≃10^5	V≃0.1mgad d≃0.2mm η≃1	1
Slow Sand Filtration	Biopolymers in Schmutzdecke	10^{-3}	L≃4ft d≃0.3mm (L/d)≃10^4	v≃3mgad d≃0.3mm η≃10^{-1}	1
Rapid Sand Filtration	Alum	10^{-1}	L≃2ft d≃0.5mm (L/d)≃10^3	v≃2gpm/ft^2 d≃0.5mm η≃10^{-2}	1
Ultra-high Rate Filtration	Alum plus Polymers	1	L≃4ft d≃5mm (L/d)≃10^2	v≃4-10gpm/ft^2 d≃5mm η≃10^{-3}	1

*Stability factors cannot be measured directly. The values presented here are based on the authors' evaluation of available literature.

**Estimates of the single collector efficiency are based upon the filtration model of Yao, Habibian, and O'Melia (5).

particles do not adhere effectively to the filter media. It is reasonable to consider that most contacts do not result in attachment; α_F is in the order of 10^{-5}, meaning that only 1 particle out of every hundred thousand that strike the filter media is actually removed. Effective filtration is accomplished by providing many collectors ($L/d \approx 10^5$) and by achieving efficient mass transport ($\eta \approx 1$). The overall value of the dimensionless product is about 1.

Higher yields and (or) smaller filters are provided by slow sand filtration. Here some partial destabilization is accomplished by the production of destabilizing chemicals on and within the filters. These destabilizing chemicals are biopolymers which are produced by microorganisms in the surface layers of the bed and which can flocculate colloids (34). Attachment is improved; α_F increases by two orders of magnitude to 10^{-3}. This chemical process permits a reduction in transport effectiveness; L/d and η are each reduced by an order of magnitude to 10^4 and 10^{-1} respectively. The dimensionless product is again about 1. Effective filtration is accomplished by trading off filter size for chemicals.

Still higher filtration rates and smaller filters are provided by conventional rapid sand filters. Here chemical pretreatment with alum is required. Attachment is again improved by chemical means, thereby permitting a reduction in transport effectiveness. The dimensionless filter product is again estimated to be about 1. The resultant trade-off of filter size for chemicals still permits effective filtration.

Alum does not provide complete destabilization. In practice this fact has led to the use of polymeric "coagulant-aids" or "filter-aids," ranging from activated silica to present synthetic organic polymers. These polymers function by improving the efficiency of particle attachment in flocculation tanks and in filter beds. When used, attachment becomes so effective that particle removal is accomplished within the uppermost portion of conventional rapid sand filter beds, resulting in excessive head losses. Polymeric filter aids therefore not only permit but actually require that transport efficiency be reduced by using larger filter media, multimedia beds, upflow filters, etc. This effective

attachment also permits the use of higher filtration rates (ultra high-rate filtration, Table 5). The product $\alpha_F \eta (L/d)$ is again about 1. Polymer is used as a trade-off for filter size. However, a limit to filter development can arise here. Particle attachment cannot be more than 100 per cent effective ($\alpha_F \simeq 1$). It is probable that the use of alum and polymers produces virtually complete destabilization. Further trade-offs between chemical and filter costs are not possible. Complete destabilization can permit the use of large media ($d \simeq 5mm$, $L/d \simeq 10^2$), and high filtration rates ($v \simeq 4\text{-}10 gpm/ft^2$, $\eta \simeq 10^{-3}$), but additional reduction in particle contact opportunities cannot be accomplished by increasing the effectiveness of the chemical component of the process. The continuing development of the filtration process from infiltration galleries where no chemicals are used ($\alpha_F \simeq 10^{-5}$) and transport is very effective ($n \simeq 1$) to ultra-high rate filters in which chemicals are very effective ($\alpha_F \simeq 1$) and transport is reduced ($\eta \simeq 10^{-3}$) is completed.

SECTION VI

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SECTION VIII

LIST OF SYMBOLS

A_o^- = Total equivalent amount of anions in a polymer solution.

BOD_5 = Five-day biochemical oxygen demand.

C_o^+ = Total Equivalent amount of cations in a polymer solution.

C_o = Concentration of particles in a filter influent.

d = Size of the filter media.

d_p = Size of the particles in the filter influent.

f = Porosity of the filter bed.

G = Mean velocity gradient.

L = Bed depth of a filter.

p^{m+} = Total number of positive charges on the polymer molecules in a polymer solution.

SS = Concentration of suspended solids.

t = Time, also the detention time in a flocculation tank.

TOC = Concentration of total organic carbon.

TP = Concentration of total phosphorus.

v = Filtration rate.

V = Total volume of a polymer solution.

α_c = Sticking factor in coagulation.

α_F = Sticking factor in filtration.

η = Single collector efficiency in filtration.

ϕ = Floc volume fraction, the volume of suspended material per unit volume of suspension.